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A CLIMATOLOGICAL ANALYSIS OF TWO YEARS OF ROUTINE TRANSOSONDE FLIGHTS FROM JAPAN[1]

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ABSTRACT

A climatological analysis is made of Navy-sponsored 300-mb. and 250-mb. constant-level balloon (transosonde) flights launched from Iwakuni, Japan, between September 1957 and April 1959. Since the transosonde naturally provides information in a Lagrangian frame of reference, treated are the trajectories and trajectory dispersion, the magnitudes and periodicities of the velocity and ageostrophic velocity components derived from the trajectories, and the separation between pairs of transosondes as a function of time after their release. In addition to the research benefits, the usefulness of transosondes in providing routine upper-wind data over the oceans is pointed out.

1. INTRODUCTION

Between September 1957 and April 1959, the United States Navy launched transosondes on an operational basis from the Naval Air Station at Iwakuni, Japan. A previous article [1] gave some preliminary results based on the first 6 months of transosonde operation. The purpose of this article is to discuss the more purely climatological results obtained from the full 2 years of operational transosonde flights.

2. THE TRANSOSONDE SYSTEM

The transosonde balloon in use between 1957 and 1959 was 40 feet in diameter and had a volume of about 34,000 cubic feet. The natural floating level of this non-expansible balloon was determined by the balance between buoyancy force (a function of environmental temperature) and the total weight of the system. Owing to the continual loss of helium through the skin of the balloon, the transosonde could be maintained at constant elevation only by means of a ballast system activated by a barograph. Of the 700 pounds carried to 300 mb. by this balloon, over 400 pounds consisted of ballast. A tendency for the natural floating level of the transosonde to rise as ballast was dropped, was counteracted in 1958 by the addition of a fan which mixed air with the helium within the balloon and thus reduced the lift. With the addition of the refinement, the transosondes seldom deviated more than 1000 feet from their prescribed flight altitude.

For the purpose of telemetering information, each transosonde was equipped with a 50-watt transmitter which operated for 15 minutes every 2 hours at alternate frequencies of 6, 13, and 19 megacycles per second. The transosonde position was determined by means of radio direction finding (RDF) bearings on these signals. This positioning was carried out by 20 RDF stations of the Federal Communications Commission located within the United States (including Alaska and Hawaii) and by the two RDF networks of the U.S. Navy in the Pacific Ocean area. The bearings taken by individual RDF stations were analyzed in Washington, D.C., and Pearl Harbor, Hawaii, and a most probable transosonde position was determined to the

[1] This work was supported by the U.S. Navy, Bureau of Aeronautics and Naval Research Laboratory in connection with a transosonde problem.

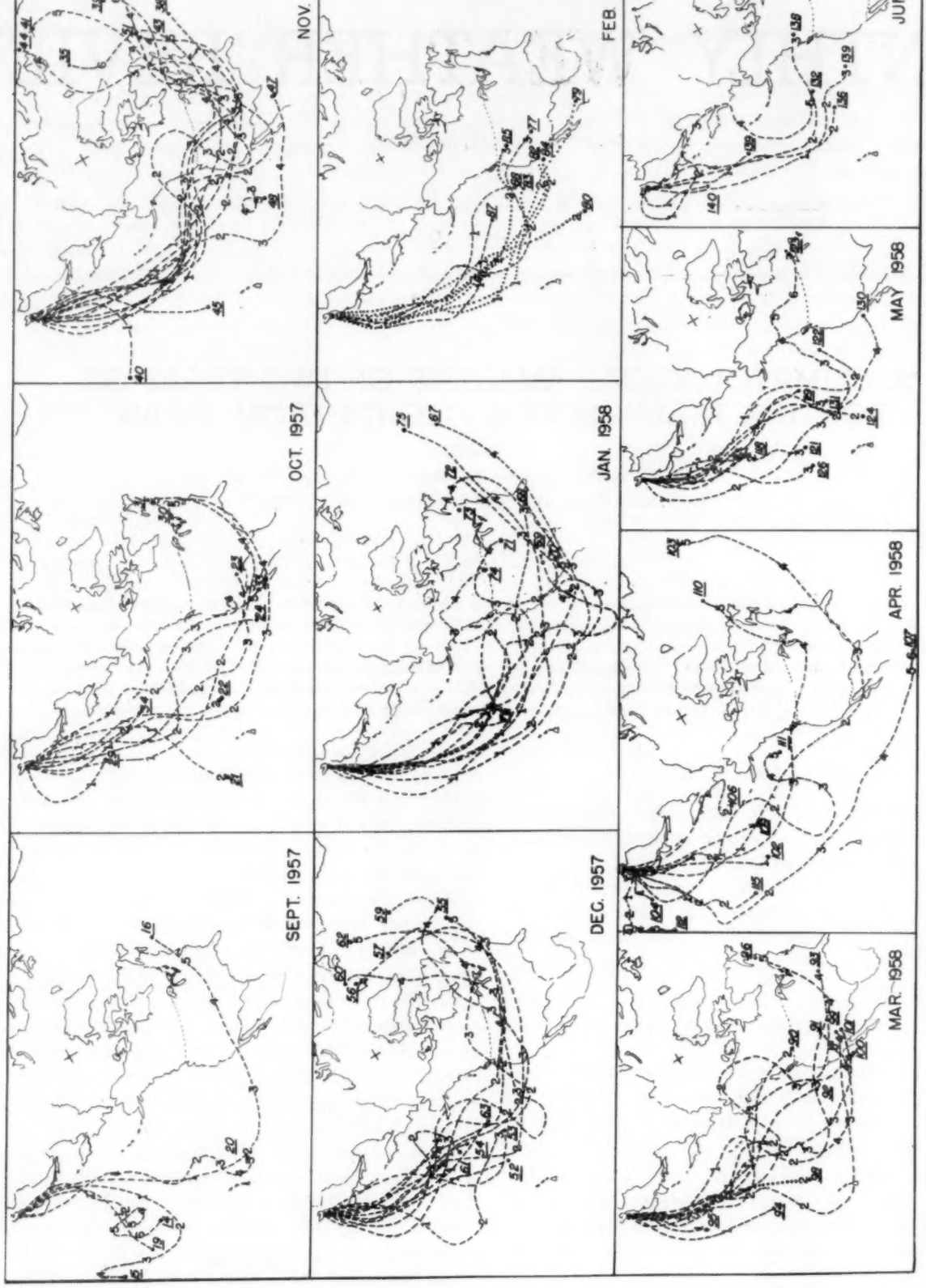

FIGURE 1.—Transosonde trajectories, for flights of one or more days duration, from September 1957 to June 1958. Dashed trajectories represent flights at 300 mb., dotted trajectories flights at 150 mb. The underlined numbers at ends of trajectories are flight designators, while numbers along trajectories indicate days elapsed after transosonde release.

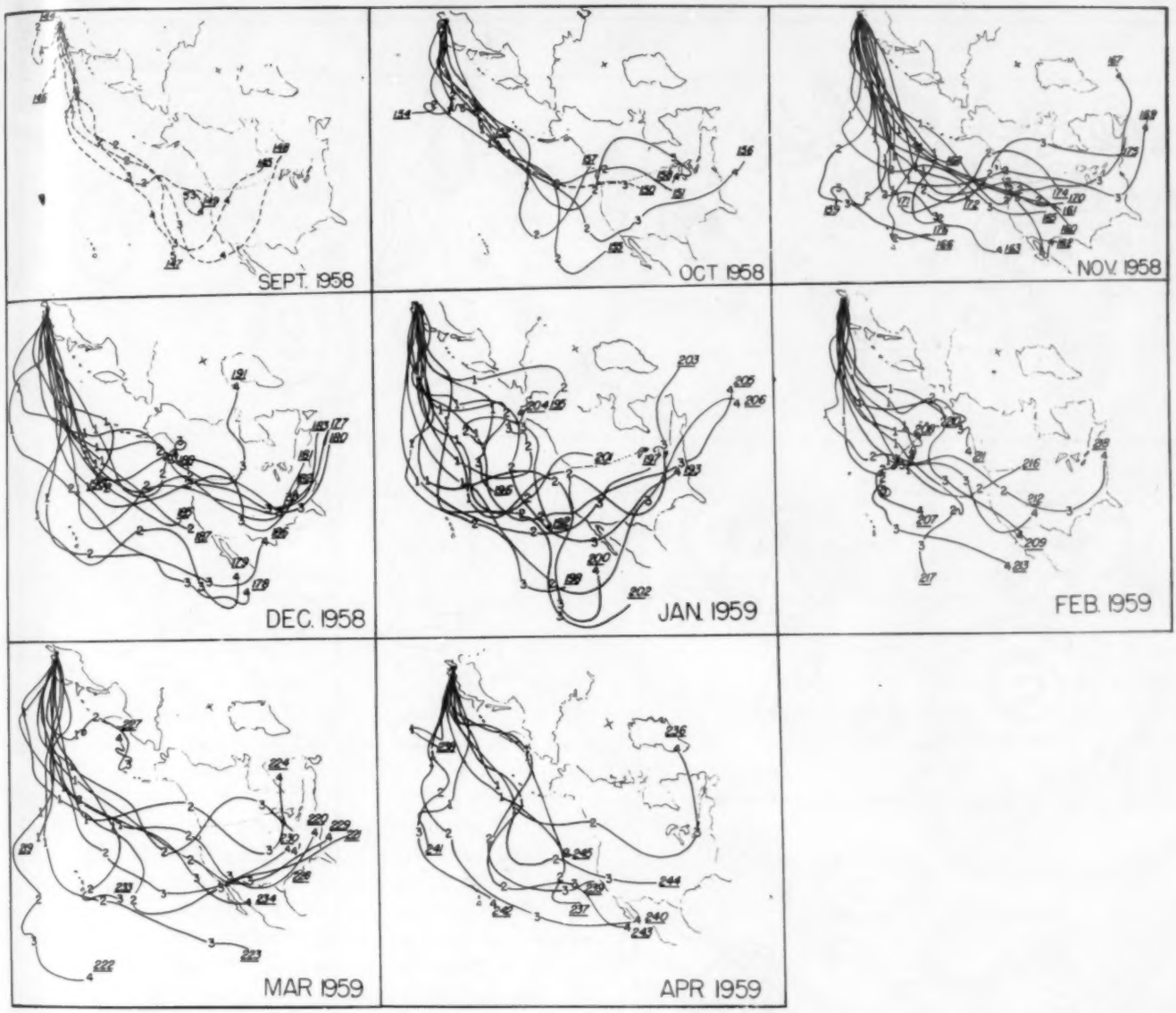

FIGURE 2.—Transosonde trajectories, for flights of one or more days duration, from September 1958 to April 1959. Dashed trajectories represent flights at 300 mb., solid trajectories flights at 250 mb.

nearest 0.1 degree of latitude and longitude. In addition, a rating of accuracy was given each fix based on the area of intercept of the bearings. All calculations of the wind and derived parameters, presented in this paper, are based upon the distance and direction traveled by the transosondes as a function of time, as determined from sequential transosonde positions obtained from the RDF networks.

3. TRAJECTORIES AND TRAJECTORY DISPERSION

Figures 1 and 2 show the trajectories of those transosonde flights which were tracked and positioned by the RDF networks for one or more days. The flights at 150 mb. during February 1958, served to test the suitability of the transosonde system for flights at levels where, in the foreseeable future, there would be no interference with commercial jet aircraft. The change in the usual transosonde flight level from 300 mb. to 250 mb. in October 1958 was brought about by a similar change in the pressure surface analyzed by the National Weather Analysis Center (NAWAC).

It is seen from figure 1 that in November 1957, flight 44 was over Great Britain 4 days after release from Japan, yielding an average speed along the trajectory of 105 knots. Because of the rapid eastward movement of the transosondes during November 1957, and the complaints of certain nations with regard to overflying Eurasia with such balloons, the flight duration during the winter months of 1957–58 was pre-set at 5 days, even though flights of 7 days duration were quite feasible. During the winter of 1958–59 the transosonde flights were limited to 4 days duration in order to avoid interference with the activities of commercial jet aircraft over the Atlantic Ocean. Of

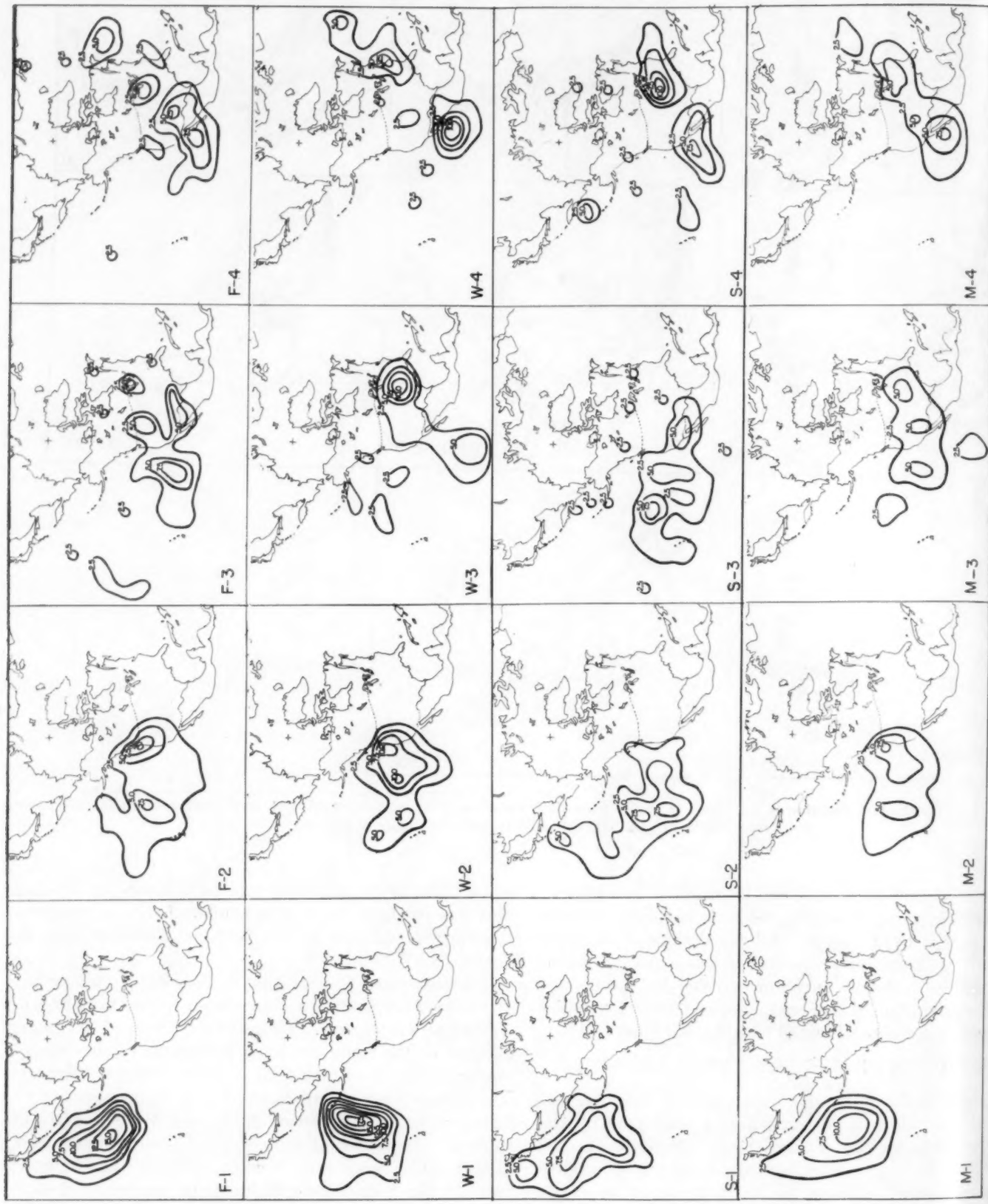

FIGURE 3.—Percentage of transosondes released which were located within 10-degree latitude-longitude "boxes" a given number of days after release for fall (F), winter (W), spring (S), and the mean (M) of all flights.

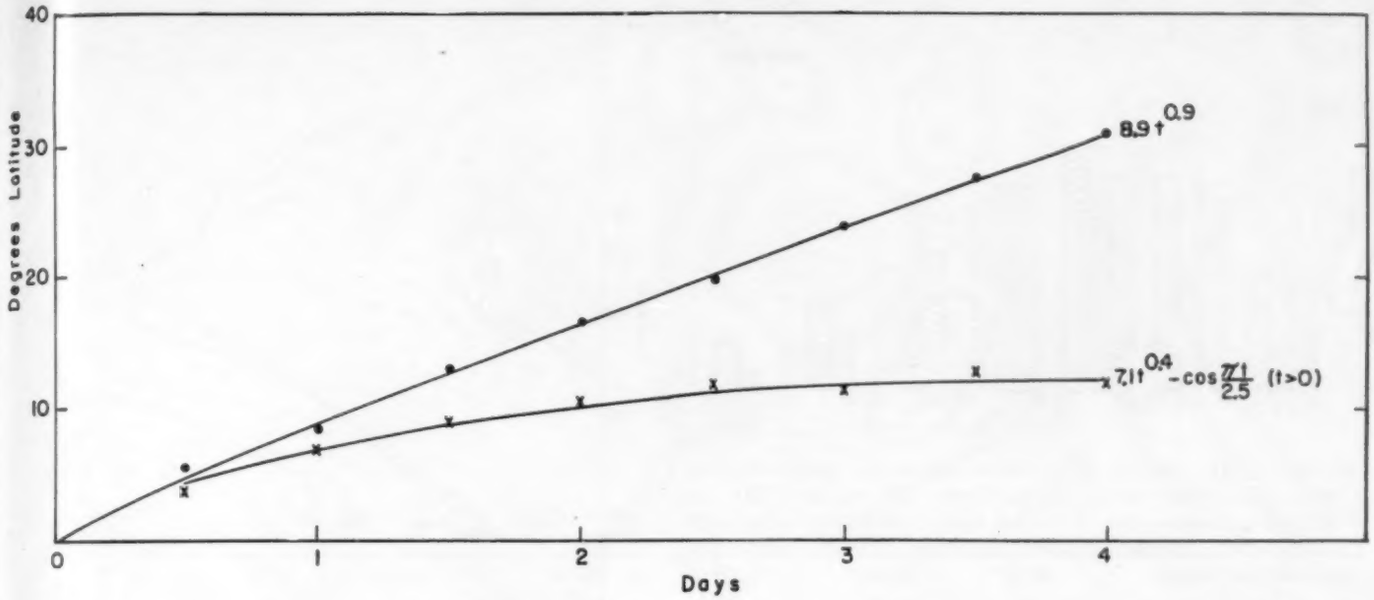

FIGURE 4.—Mean latitudinal (crosses) and longitudinal (dots) standard deviations of position as a function of time after transosonde release for all 1957–1959 flights of four or more days duration. The lines represent the fit of the indicated analytic expressions to the observed values (t in days).

the 230 transosondes released during these 2 years, 179 were tracked and positioned by RDF stations for at least 1 day, 152 for at least 2 days, 116 for at least 3 days, and 83 for at least 4 days.

Figure 3 shows the (smoothed) percentage of transosondes released which were located within 10° latitude-longitude "boxes" from 1 to 4 days after release from Japan. In the mean for all flights, the maximum percentages are located near 180° longitude 1 day after release and just to the west of the State of Washington 2 days after release. Three days after release, in the mean for all flights, the band of maximum percentage extends from 140° W. to the Mississippi River, while 4 days after release the maximum percentages are centered over the State of Kentucky and an area somewhat to the west of Baja California. One would judge from figure 3 that in all three seasons there are two dominant circulation patterns over the northeastern Pacific and North America, one of which carries the transosondes eastward across the United States while the other carries the balloons into a transosonde "graveyard" to the west of Baja California. This tendency for transosondes to congregate near Baja California, is of practical importance since many storms influencing southern California and Arizona are difficult to position owing to the lack of conventional upper-air data in this region. Also of interest in figure 3 is the concentration in transosonde position 1 day after release during winter which indicates the steadiness of the wintertime winds over and to the east of Japan.

Values of the latitudinal and longitudinal standard deviation of transosonde position a given number of days after release were determined by direct evaluation of the root mean square of the latitudinal and longitudinal distances between mean and individual flight positions for all 300-mb. and 250-mb. flights of four or more days duration. Figure 4 shows these latitudinal (crosses) and longi-

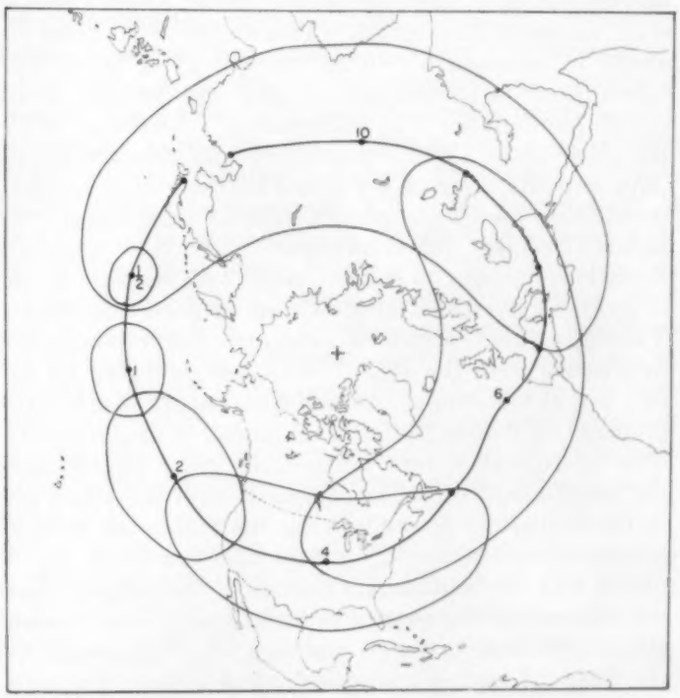

FIGURE 5.—Ellipses delineating the areas within which observations and computations indicate 50 percent of the transosondes are to be found a given number of days after release from Iwakuni, Japan.

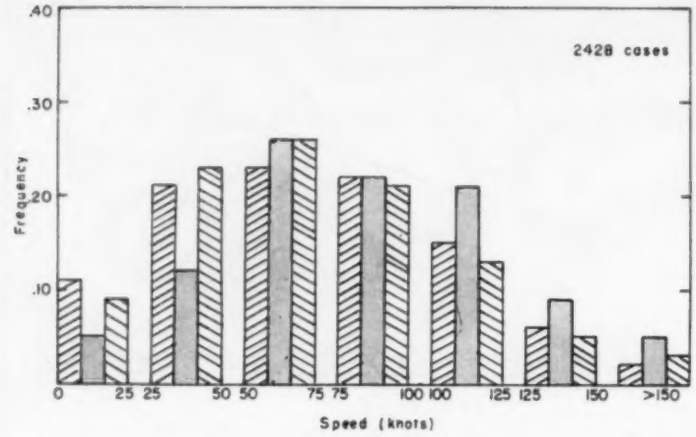

FIGURE 6.—Distribution of 6-hour-average wind speeds obtained from 1957–1959 transosonde flights at 300 mb. and 250 mb. Within each class interval the left hand, middle, and right hand columns give, respectively, the frequencies for flights during fall, winter, and spring.

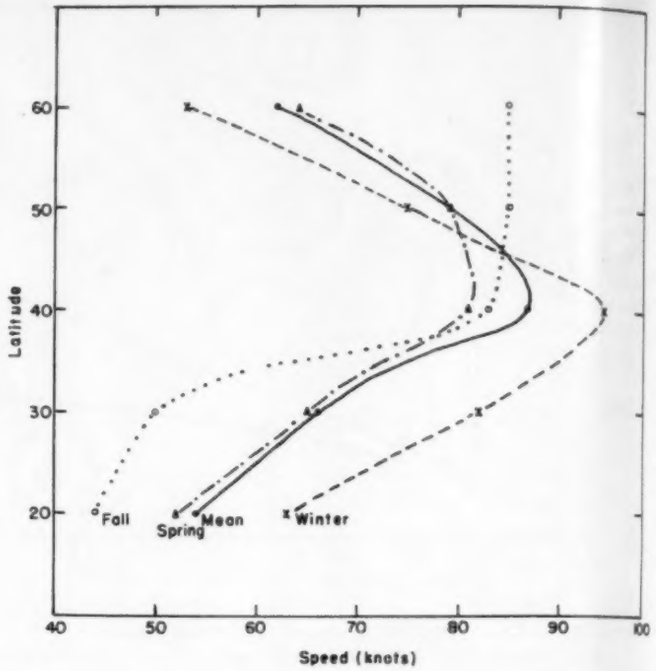

FIGURE 7.—Transosonde-derived wind speed as a function of latitude for the three seasons and the mean of all flights.

tudinal (dots) standard deviations as a function of time after transosonde release. The values plotted are the means of the standard deviations (in degrees latitude) determined separately for fall, winter, and spring. The lines in the diagram represent the fit of the indicated analytic expressions to these values. It is seen that the longitudinal standard deviation increases almost linearly with time after release, whereas the latitudinal standard deviation increases more slowly with some evidence for the superposition upon the power variation of a small-scale sinusoidal fluctuation. This sinusoidal fluctuation would be associated with the tendency for latitudinal bunching of the transosondes as they approach the mean trough positions near the east coasts of continents. With the aid of these analytic expressions the standard deviations of position can be estimated for time intervals after transosonde release exceeding 4 days. Figure 5 shows, by means of ellipses, the areas within which these standard deviations indicate 50 percent of the transosondes would be located a given number of days after release from Japan. The ellipses are centered on a mean wintertime trajectory determined from the 1957–59 transosonde flights for the first 4 days following release and from mean 300-mb. maps prepared by Brooks [2] for the remainder of the trajectory. This figure makes more obvious the great dispersion in the longitudinal direction compared with the dispersion in the latitudinal direction when the flights are grouped by season. As a result, 10 days after release it is estimated that the latitudinal extremes of the ellipses would not fall outside the zone of prevailing westerlies, whereas the longitudinal extremes embrace all of Eurasia. On the basis of earlier transosonde flights, launched from Minneapolis, Minn., and Japan, Edinger and Rapp [3] found larger latitudinal and smaller longitudinal standard deviations of position as a function of time after release than found here.

4. MAGNITUDE OF VELOCITY AND AGEOSTROPHIC VELOCITY

Transosonde-derived wind speeds were obtained from distances between smoothed transosonde positions 6 hours apart. The smoothed positions were obtained by the averaging of three successive latitude and longitude determinations 2 hours apart. Figure 6 shows the distribution by season of the 6-hour-average wind speeds so obtained. For all three seasons the speed mode is 50–75 knots. However, in winter 35 percent of the wind speeds exceed 100 knots whereas in fall and spring only about 23 percent of the speeds exceed this value. In winter 5 percent of the speeds exceed 150 knots. This percentage would doubtless be higher except for the considerable reduction in peak wind speeds brought about by the use of 6-hour-average winds derived from smoothed positions.

Figure 7 shows the transosonde-derived wind speed as a function of latitude for the three seasons and the mean of all flights. In the mean the wind speed is shown to be a maximum just north of latitude 40°. Rather surprisingly, during the fall the transosonde-derived wind speeds are strongest far to the north. It must be remembered, however, that since the transosondes were launched from a single location, they were sampling ridge conditions in the north and trough conditions in the south. Since it has been found from the transosonde flights that in the average the speed is stronger on ridges than in troughs (fig. 11), a bias easily may be introduced. Along this line, it may be noted that in winter the transosonde-derived wind speed is a maximum considerably north of latitude

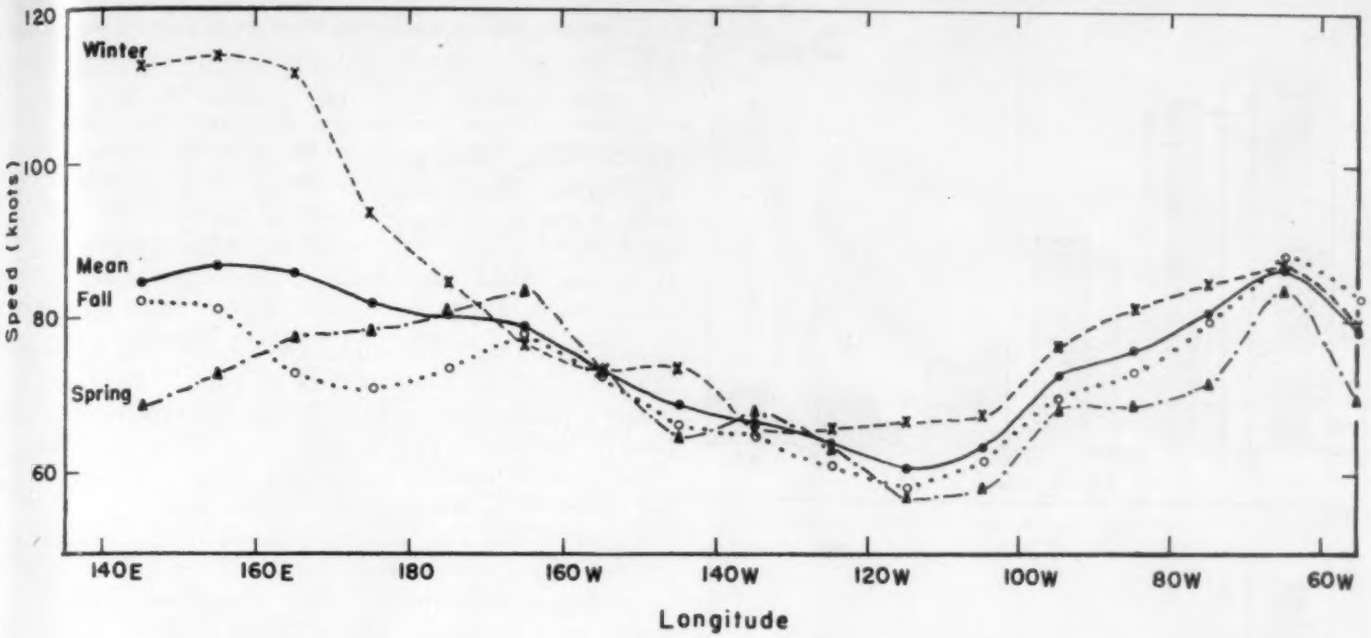

FIGURE 8.—Transosonde-derived wind speed as a function of longitude for the three seasons and the mean of all flights.

30° where the zonal geostrophic wind apparently has its hemispheric maximum [4]. This could be a result of a geostrophic wind bias (wind in the trough always subgeostrophic), the fact that the transosondes sample ridges at latitude 40° and troughs at latitude 30°, or a geographical bias due to the comparison of winds over a portion of the hemisphere with winds around the entire hemisphere

Figure 8 shows the transosonde-derived wind speed as a function of longitude for the three seasons and the mean of all flights as determined over a limited latitude range. Impressive is the magnitude of the wind speed just to the east of Japan during the winter. However, in spring the maximum wind speed is located near 165° W. rather than near Japan. It is of interest that from 180° longitude to the west coast of North America the wind speed is nearly the same during all three seasons, whereas the diagram illustrates the well-known fact that over North America the wind speed is greater in winter than in fall or spring.

Figure 9 gives the distribution of 12-hour-average "natural" ageostrophic components obtained from the 2 years of transosonde flights. These components were evaluated through the equations of motion utilizing accelerations derived from transosonde velocity changes in 12 hours. The exact manner in which these cross-contour ($V \sin i$) and along-contour ($V \cos i - V_g$) components of the ageostrophic wind are obtained from transosonde data is reported in [5]. For both ageostrophic components the mode is 0–5 knots while about 4 percent of the cross-contour and 15 percent of the along-contour components of the ageostrophic wind exceed 25 knots. In the mean, the cross-contour component of the ageostrophic wind is about two-thirds the magnitude of the along-contour component. From comparison of the average values of these ageostrophic components with the values of the wind speed shown in figure 6, it is estimated that in the average the ageostrophic wind is nearly one-fourth the magnitude of the wind itself.

Of importance in the study of the meridional momentum flux is the product of zonal-meridional wind components and their geostrophic and ageostrophic parts. Since zonal and meridional ageostrophic velocity components are easily obtained from zonal and meridional components of transosonde acceleration, the transosondes offer a feasible means for evaluating the contribution of ageostrophic winds to the meridional transport of momentum. Table 1 gives the mean seasonal values for the products of interest. The mean value of the zonal-meridional wind product for the 2 years of data is 310 kt.^{2}, corresponding to a mean correlation between zonal and meridional wind components of 0.21. Integrating around the hemisphere at latitude 35° N. during January, Mintz [6] found an average (geostrophic) value of 285 kt.^{2}. Especially noteworthy in table 1 is the sum of the products involving ageostrophic terms, as shown in the next to the last column These sums are almost 10 percent of the wind products

TABLE 1.—*Magnitude of zonal-meridional wind and geostrophic-ageostrophic wind products derived from 2 years of transosonde flights (kt.^{2})*

	$\overline{uv}$	$\overline{u_g v_{ag}}$	$\overline{u_{ag} v_g}$	$\overline{u_{ag} v_{ag}}$	Sum of ageostrophic products	Cases
Fall	284	2	29	−9	22	611
Winter	260	−11	3	−20	−28	743
Spring	393	41	32	−49	24	637
Mean	310	12	21	−26	7	1991

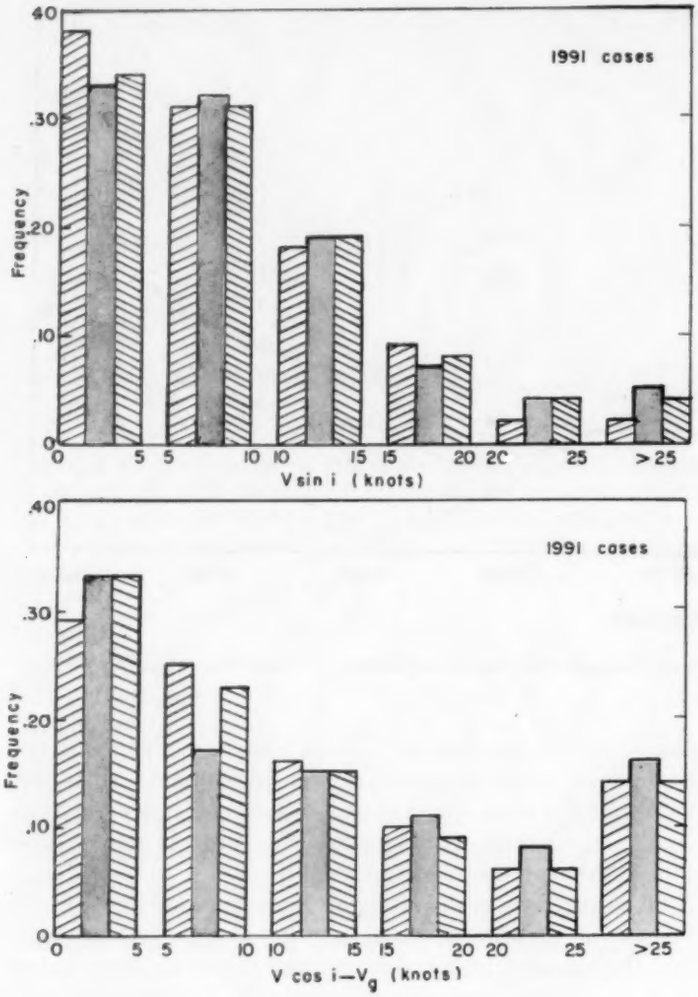

FIGURE 9.—Distribution of 12-hour-average cross-contour ($V \sin i$) and along-contour ($V \cos i - V_g$) components of the ageostrophic wind obtained from 1957–1959 transosonde flights at 300 mb. and 250 mb. Columns indicate frequencies for fall, winter, and spring, from left to right as in figure 6.

themselves and suggest that in winter the ageostrophic products counteract the northward meridional flux of momentum associated with the geostrophic winds whereas in fall and spring they augment this flux. This result may be associated with the seasonal shift of the jet stream as suggested by the theoretical work of Lorenz [7].

5. PERIODICITIES AND CORRELATIONS FOR VELOCITY AND AGEOSTROPHIC VELOCITY PARAMETERS

A crude estimate of the predominant periodicity in the fluctuations of velocity and ageostrophic velocity parameters was obtained by multiplying by two the length of time for which the deviation of the parameter from the mean value for the flight maintained the same sign. For example, if the meridional wind component were positive (south wind) for three successive 6-hour time intervals, the period would be entered as 36 hours. It should be noted in passing that errors in transosonde positioning will tend to introduce a 12-hour periodicity in the transosonde velocity, as determined here, and a 24-hour periodicity in the ageostrophic wind, as determined here.

TABLE 2.—*Correlation coefficients among velocity and "natural" ageostrophic velocity components based on 2 years of transosonde flights*

Correlation between:	Fall	Winter	Spring	Mean
Zonal and meridional wind	0.258	0.135	0.288	0.211
Zonal wind and along-contour component of ageostrophic wind	.236	.055	.085	.112
Meridional wind and cross-contour flow	.321	.136	.056	.128
Cross-contour flow and along-contour component of ageostrophic wind	−.040	.003	−.057	−.025
Cases	611	743	637	1991

Figure 10 shows the results obtained by this method for the meridional velocity component and the two "natural" ageostrophic components. The meridional wind fluctuates most frequently with a period of about 41 hours, which indicates the most frequent time needed for a 300-mb. or 250-mb. transosonde to transit a long wave in the westerlies. The cross-contour component of the flow ($V \sin i$) fluctuates most frequently with a period of about 23 hours. It is not certain, however, to what extent this represents a real periodicity in this component since, as mentioned above, an error in transosonde positioning would introduce such a period of fluctuation. Further work along this line using ageostrophic components averaged over a shorter time interval is indicated, since the inertial period corresponding to the mean latitude about which the transosondes oscillated is 20 hours and thus we may have evidence here for inertial oscillations. The along-contour component of the ageostrophic wind fluctuated most frequently with a period of about 30 hours as if reflecting both the long-wave period of 41 hours and the cross-contour-flow period of 23 hours. Similar computations were carried out for the zonal wind component and the wind speed but they are not presented here since they showed no pronounced short-period fluctuation, perhaps due to the fact that the deviations from the mean for these parameters reflect the long-period (4 days or more) periodicity in the transosonde wind associated with the passage of the transosonde from the region of strong winds over Japan to the region of strong winds over the northwestern Atlantic (fig. 8).

Table 2 shows the correlation coefficients among certain velocity and ageostrophic velocity parameters for the season and the mean of all flights. According to the "Z test" presented in Hoel [8], with the number of cases here available, a correlation of 0.05 is significant at the two-sigma level in the mean and a correlation of 0.08 is significant at the two-sigma level for the seasonal data.

As would be expected, the zonal and meridional wind components are significantly positively correlated in all three seasons with the correlation most pronounced in fall

and spring. The zonal wind and along-contour component of the ageostrophic wind are positively correlated in all three seasons (fall and spring significant) as are the meridional wind and the cross-contour component of the ageostrophic wind (fall and winter significant). The correlation between the two ageostrophic wind components is negative in fall and spring and slightly positive in winter, but none of the correlations is significant. Since, along an idealized wave-shaped trajectory, the meridional wind component would be a maximum at the pre-trough inflection point and the along-contour component of the ageostrophic wind would be a maximum at the trajectory crest, the relative magnitudes of the above correlations yield estimates of where in the wave-shaped flow pattern the maximum zonal wind and maximum flow toward low pressure occur on the average. Based on such reasoning, figure 11 shows that during all three seasons the maximum zonal wind is located about halfway between pre-trough inflection point and trajectory crest while the maximum flow toward low pressure occurs near the pre-trough inflection point, with some doubt as to whether it occurs just upstream from or just downstream from this point.

6. ESTIMATION OF THE MEAN TRANS-PACIFIC MERIDIONAL FLOW

The existence of a mean meridional cell in the Tropics (Hadley Cell) has been confirmed by wind measurements and estimates of the angular momentum balance. However, the sense, or even existence, of a meridional cell in temperate latitudes (Ferrel Cell) is still in dispute. It is shown below how the changes in height of a constant-pressure surface at successive transosonde positions permits the estimation of the mean meridional flow over a limited portion of the hemisphere.

The change in height of a constant-pressure surface along a transosonde trajectory can be estimated according to the equation

$$\Delta z=\int_{t_1}^{t_2}\frac{\partial z}{\partial t}\,dt-\frac{V_2^2-V_1^2}{2g}-\frac{1}{g}\int_{t_1}^{t_2}Vw\frac{\partial V}{\partial z}\,dt \qquad (1)$$

where Δz is the height change following the transosonde, $\partial z/\partial t$ is the local height change along the trajectory, V_2 and V_1 are transosonde speeds at two different times t_2 and t_1, g is the acceleration of gravity, w is vertical air motion, and $\partial V/\partial z$ is vertical wind shear [9]. The term involving the local height change may be large on individual flights, but since it is not likely to have an average much different from zero for flights released almost randomly from Japan, it will be set equal to zero in this discussion. Moreover, while the term involving the vertical velocity may be important along isolated trajectory segments, it was found to be of negligible magnitude in the mean for many flights due to the very small value for the trans-Pacific vertical velocity determined by the adiabatic method (0.1 cm. sec.$^{-1}$).

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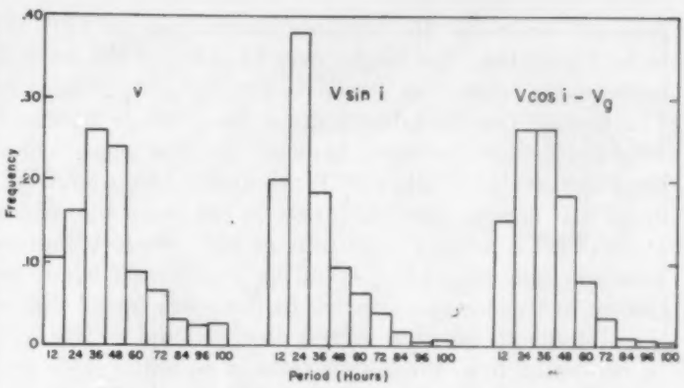

FIGURE 10.—Distribution of periods of fluctuation for meridional wind component (v), cross-contour flow (V sin i), and along-contour component of ageostrophic wind (V cos $i-V_g$).

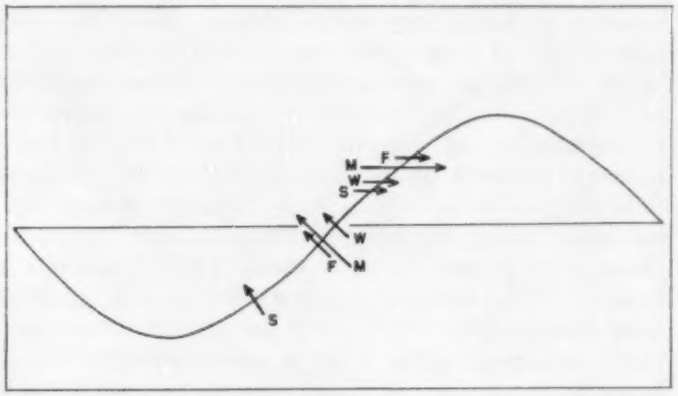

FIGURE 11.—Positions along schematic wave-shaped trajectory of maximum zonal wind (horizontal arrows) and maximum flow toward low pressure (arrows normal to trajectory) for fall (F), winter (W), spring (S), and the mean (M) of all flights.

The top row in table 3 gives the change in height of the constant-pressure surface between Iwakuni and the place where the transosonde transits 120° W. longitude which would be expected due to the change in speed along the individual transosonde trajectories (middle term in equation (1)). Since the transosondes slow down while crossing the Pacific, one would expect the height of the constant-

TABLE 3.—*Computed and observed trans-Pacific height changes (in feet) of constant pressure surfaces along transosonde trajectories and derived mean meridional ageostrophic flow*

	Fall	Winter	Spring	Mean
Height at 120° W. minus height at Iwakuni derived from change in transosonde speed	170	450	180	290
Height at 120° W. minus height at Iwakuni obtained from 300 mb. and 250 mb. NAWAC maps	−390	220	−100	−50
Height discrepancy in radiosondes (Japanese minus United States)	130	130	130	130
Observed height difference minus computed height difference	−430	−100	−150	−210
Derived mean meridional flow (knots)	3.1	0.9	1.2	1.6
Number of evaluations	27	40	27	94

pressure surface at the transosonde position at 120° W. to be higher than the height over Iwakuni at the time of transosonde release, as shown in the top row of table 3. The second row in table 3 gives the average observed height difference between Iwakuni and the place where the transosonde transits 120° W. as obtained from NAWAC maps. It is most surprising that in the mean the height at Iwakuni is greater than that at 120° W. in complete contradiction with what would be anticipated from the change in transosonde speed. In the mean for all flights the discrepancy between what is observed and what would be computed from the middle term in equation (1) is 340 feet. Part of this discrepancy is due to the incompatibility of United States and Japanese radiosondes, as found at Payerne and reported by Harmantas [10]. According to the Payerne tests, the Japanese 300-mb. and 250-mb. heights should average about 130 feet more than those reported by United States radiosondes. Since the existence of a mean floating level for the transosondes slightly above the constant-pressure surface in question was found to have no influence on the above calculations, unless the incompatibility of Japanese and United States radiosondes is greater than determined at Payerne, the above data suggest the presence of a mean northward ageostrophic flow at 300 mb. and 250 mb. above the Pacific Ocean of magnitude given by the next to the last row in table 3. These meridional velocity components in table 3 were evaluated by determining the meridional displacement corresponding to a given pressure-height change based on the average meridional distance between 300-mb. and 250-mb. contours as estimated from the zonal component of transosonde velocity. Since it is not known what transosonde flights over the remainder of the hemisphere would yield with respect to the sense and magnitude of meridional ageostrophic flow, the resolution of the meridional-cell problem awaits the extension of the flights to Eurasia.

7. TRANSOSONDE DENSITY AS A FUNCTION OF TIME AFTER RELEASE

For the purpose of studying the transosonde density a given number of days after release for transosondes released from the same point at different times, the number of transosonde pairs at various distances apart was determined by season for the 1957–59 transosonde flights from Japan. The approach resembles Richardson's distance-neighbor technique except that, instead of determining the temporal variation of the distance separating pairs of air parcels in the air at the same time, here we determine the variation with time since release of the distance separating pairs of transosondes in the air at different times. Certainly results obtained utilizing data of the latter type need not be representative of the results which would be obtained using data of the former type.

Figure 12 shows the percentage of possible transosonde pairs which were located (within 5-degree latitude bands)

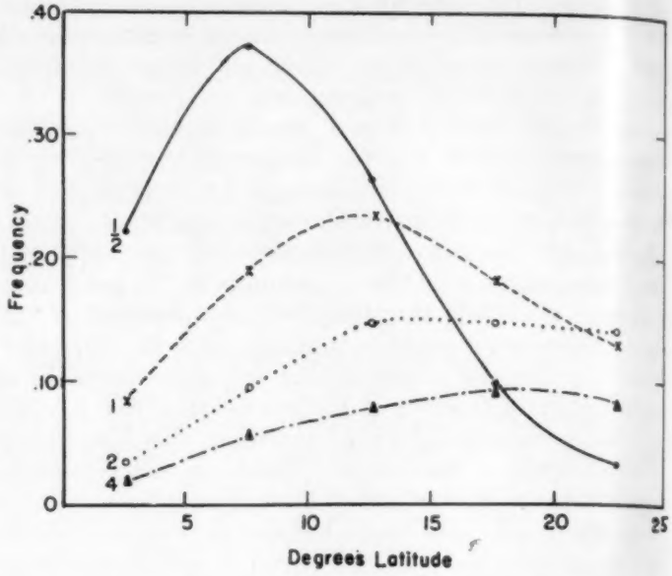

FIGURE 12.—Distribution of distances between all possible transosonde pairs as a function of time in days after their (non-simultaneous) release.

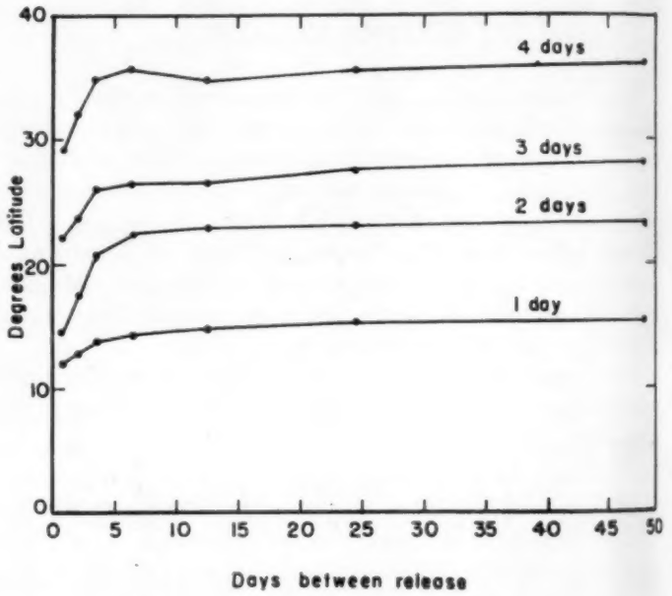

FIGURE 13.—Average geographical distance between all possible transosonde pairs a given number of days after release as a function of time interval between release of transosondes making up the pair (abcissa).

a given number of degrees latitude apart a certain number of days after release from Japan, as obtained by averaging the results derived for the three seasons of fall, winter, and spring. This diagram shows, for example, that 1 day after transosonde release 23 percent of the possible transosonde pairs are 10°–15° latitude apart, while 4 days after transosonde release 8 percent of the possible pairs are separated by this distance. With an average error in

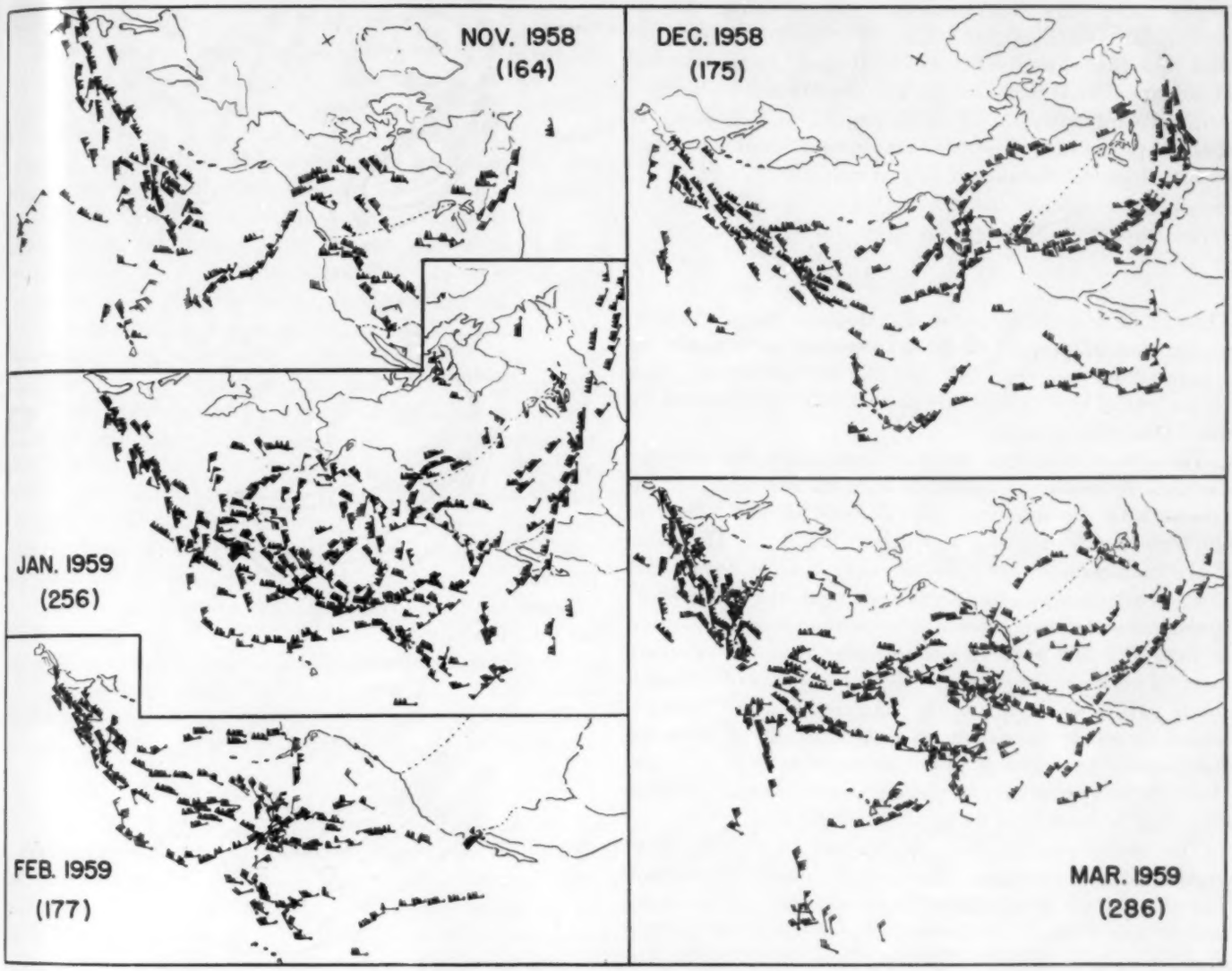

FIGURE 14.—Transosonde-derived winds plotted on NAWAC 250-mb. maps between November 1958 and March 1959. Numbers in parenthesis give the total plottings for each month.

percentage of 0.03 in the 20 plotted positions given in figure 12, the percentage of possible transosonde pairs (P) separated by a given number of degrees latitude (R) a given number of days after release from Japan (t) is given analytically by

$$P=40\ tR^{-2.2}e^{\frac{-25t}{R^{1.2}}}dR \qquad (2)$$

where dR is the latitude interval under consideration (5° in fig. 12).

Differentiating equation (2) with respect to R and setting the resultant equal to zero it is found that the most frequent distance (mode) between balloon pairs (R_m) is given by

$$R_m=8.8\ t^{0.833} \qquad (3)$$

where t is in days and R_m is in degrees latitude. Thus, 7 days after transosonde release it is estimated that the most frequent separation of pairs of transosondes would be 45° of latitude with, from equation (2), 11 percent of the possible transosonde pairs being separated by 40°–50° latitude. It is interesting that, with the replacement of the time coefficient in equation (3) by the value 5.8, this equation almost exactly satisfies the average distance between 700-mb. geostrophic-trajectory pairs initiated from a point at 2-day intervals (similar to the transosondes) during the period April-June 1948, as reported in a paper by Durst et al. [11]. Thus there is independent evidence in support of the power of the time given in equation (3). Theoretical considerations presented by Durst et al. indicate that, if it is assumed that the autocorrelation coefficient is exponential in form, the average distance between trajectory pairs should increase nearly linearly with time initially and increase according to the square root of time

two or more days after initiation. If anything, the experimental results suggest a quicker trajectory separation with time than does the theory based upon the assumption of an exponential form for the autocorrelation coefficient.

Integrating equation (1) with respect to R it is found that the percentage of possible transosonde pairs separated by less than the distance R (P_R) is given by

$$P_R=\frac{4}{3}e^{\frac{-2R}{R^{1.2}}} \tag{4}$$

Thus, 7 days after transosonde release it would be estimated that 27 percent of the transosonde pairs would be separated by less than 50° latitude or, conversely, that 73 percent of the transosonde pairs would be separated by more than this amount.

The above equations are not exact since the average distance between the elements of a transosonde pair increases with the time interval (T) between the release of the transosondes making up the pair (fig. 13). However, if the transosondes are released more than 6 days apart there is little increase in the average separation as a function of time between release. Since the results presented in figure 12 are based upon seasonal data, the average interval between the release of the components of a transosonde pair is 45 days. If the transosondes had been released in quick succession so that the interval between transosonde release was, in the average, only 2 days say, then a larger percentage of the transosonde pairs in figure 12 would be separated by smaller distances.

The above analysis has application to "silent area" problems. For example, suppose that a pathfinder balloon was at a certain geographical location 2 days after release and it was desired to know the probability of getting another balloon, launched from the same site, within 10° latitude of this location 2 days after release. According to figure 12 there would be only a 13 percent chance of getting a balloon within the desired area unless the additional balloons were released soon after positioning of the pathfinder balloon, in which case the probability might jump to 15 percent or so. Thus, if seven or eight additional balloons were released, in the average it would be expected that one of these balloons would be within the required area 2 days after release. For further extension in time and space reference may be had to equation (4). For example, this equation would suggest that in order to get a second balloon within 50° latitude of the pathfinder balloon 7 days after release, on the average four additional balloons would have to be released.

8. THE USEFULNESS OF TRANSOSONDE DATA FOR OPERATIONAL WEATHER ANALYSIS

Between November 1958 and April 1959, 6-hour-average transosonde-derived winds were included in the transosonde teletypewriter messages originating at Pearl Harbor, Hawaii and Norfolk, Va. These winds were plotted in a

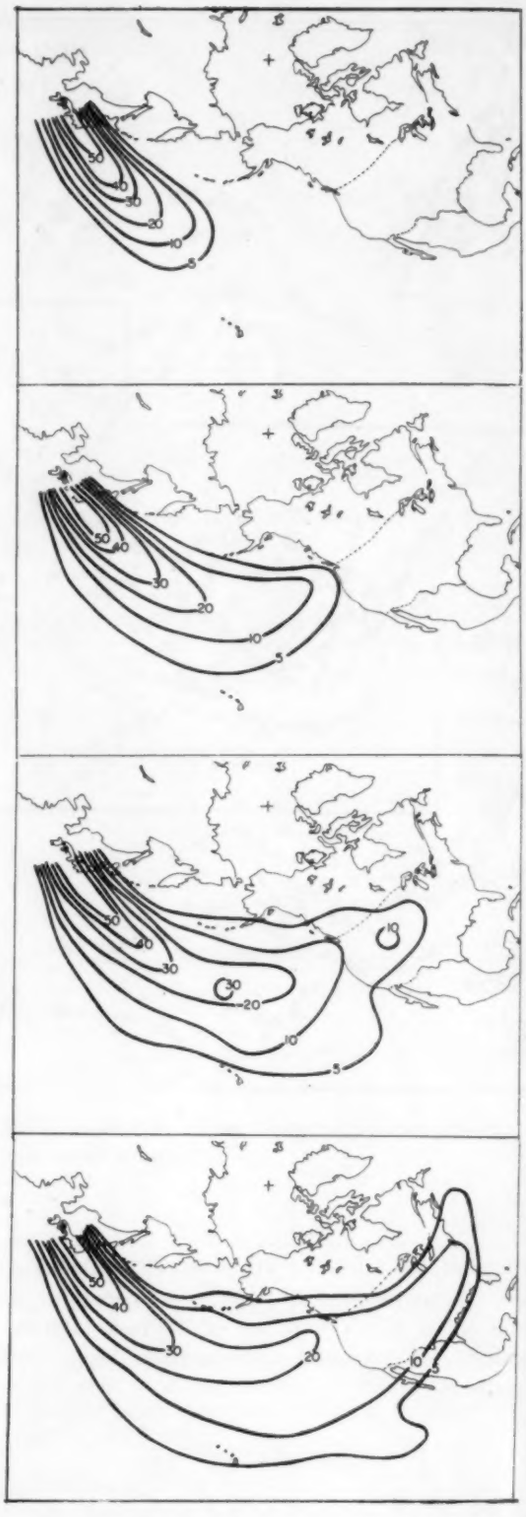

FIGURE 15.—Percentage of 1957–1959 transosondes at 300 mb. and 250 mb. passing through 5-degree latitude-longitude "boxes" within (from top to bottom) one, two, three, and four days following release.

routine fashion upon the NAWAC 250-mb. maps. Figure 14 shows the winds so plotted during five of these six months. A total of more than 1000 transosonde-derived winds was plotted during this 5-month interval, providing a rich source of information for the map analyst and forecaster. Since the tracking, communications, and plotting procedures were only operating at 50 percent efficiency during this time, twice as many winds could have been derived from the flights. For the planning of any future transosonde operation it is desirable to know what percentage of the time a transosonde released from Iwakuni would pass over a given geographical region and provide meteorological data there. Based on the 1957–1959 transosonde flights at 300 mb. and 250 mb., figure 15 shows the percentage of transosondes released which transited 5-degree latitude-longitude "boxes" within a certain number of days following release. This diagram shows, for example, that one-tenth of the transosondes released from Iwakuni would within 3 days following release, furnish meteorological information within the 5-degree latitude-longitude "box" embracing most of Wyoming. It may be noted that the highest percentages are found in just that latitude belt of the Pacific Ocean where conventional upper-air data are almost totally lacking. It seems certain that transosonde releases from Iwakuni, Japan could provide the means for obtaining much-needed upper-wind and other data over the Pacific Ocean.

9. CONCLUSION

Transosonde flights yield data of importance from both the operational and research viewpoint. Part of this importance resides in the ability of the transosondes to fill in the climatological void in regions where conventional upper-air data are sparse, such as the Pacific Ocean area. In this paper we have intentionally presented climatological data in the Lagrangian frame of reference with the hope that the meteorologist and climatologist may thereby come to realize that the Eulerian-type data now used exclusively is not the only type of data available and, indeed, is perhaps not the type of data which is most desirable. It may well be that a change in emphasis from Eulerian to Lagrangian-type data is the step needed to achieve a higher plateau of knowledge in the field of meteorology. The transosonde system offers the means by which this change in emphasis can be made a reality.

ACKNOWLEDGMENT

Mrs. Marguerite Hodges drafted the figures and performed many of the calculations upon which this paper is based.

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THE HURRICANE SEASON OF 1959

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1. GENERAL SUMMARY

Eleven tropical cyclones were noted in Atlantic waters during the hurricane season of 1959 (fig. 1). This number compares with an annual average of ten during the past 20–25 years. Since there is considerable doubt whether one storm—Edith—fully met all the criteria of a tropical cyclone, the 1959 season may be regarded as about normal. Except for hurricanes Gracie and Hannah in late September and early October, average intensity was unusually weak. However, seven of the eleven storms did reach hurricane intensity at one time or another during their history.

The season started early with the first tropical storm developing on May 28. Activity continued high during June and July. There was an unusual lack of activity in the tropical Atlantic during August and early September until Flora began to develop on September 9. Most of the tropical cyclone development was confined to the Gulf of Mexico and the western Atlantic and only one storm originally attained hurricane intensity east of longitude 50° W.

Three hurricanes—two barely of hurricane intensity—and four tropical cyclones of only storm intensity reached the coastline of the United States. Damage in the United States from these storms totaled about $23½ million with 24 fatalities, 22 resulting from Gracie, the only major hurricane to reach the United States mainland. Except for the 33 deaths and extensive damage in Nova Scotia in connection with the hurricane of June 17–21, there were no other known deaths or even significant damage in North and Central America outside the United States from tropical cyclones. Damage and fatality statistics are shown in table 1. The damage statistics are estimates and are necessarily approximate.

The May circulation pattern [1] included a mean ridge over the eastern United States, averaging as much as 150 feet above normal at 700 mb. During the period May 28–June 1, the maximum positive height anomaly over the northeastern United States was 320 feet, with height deficits southeast of Bermuda and in the western Gulf of Mexico. This resulted in above normal easterly winds which is considered favorable for above normal tropical cyclone activity. One storm developed in the central and western Gulf of Mexico on May 28. A tropical development this early in the season in the Altantic area is somewhat rare; there have been seven tropical cyclones in May since 1932.

Tropical cyclone activity continued at an above normal rate during June and July with two storms in each month; one of only storm intensity, two barely of hurricane strength, and one (Debra) of somewhat more than minimal hurricane intensity. The 700-mb. circulation in June [2] was characterized by above normal heights from the extreme southeastern Pacific across California to the western Great Lakes region, with below normal heights off the United States Atlantic coast across southern Florida into the southern Gulf and northwestern Caribbean. As a result there was deeper than normal easterly flow in the Gulf of Mexico and northwestern Caribbean. However, the resemblance between the June 1959 circulation and that described by Ballenzweig [3] as favorable for Gulf of Mexico tropical cyclone development is at best only fair.

In July a positive mean 700-mb. height anomaly was centered over the northeastern United States and the Canadian Maritime Provinces. With negative anomalies extending from the Gulf of Mexico eastward over the subtropical Atlantic [4], this resulted in an above normal easterly flow north of the axis of the negative anomaly. But again resemblance to the departure from normal described by Ballenzweig as favorable to tropical storm formation is only fair.

Tropical cyclone activity in August was negligible. At 700 mb., positive height anomalies extended from the Great Lakes region across the northern Atlantic to the Baltic Sea with a strong negative anomaly centered about 30° N., 50° W. and with a weaker departure over Cuba [5]. Thus easterlies (westerlies) should have been stronger

TABLE 1.—*Fatality and damage statistics, North Atlantic hurricane season 1959*

Storm	Principal area affected	Deaths in United States	Deaths outside United States	Damage
Arlene	Louisiana	1	0	$500,000
Unnamed	Nova Scotia	0	33	Considerable
	Southern Florida	0	0	1,656,000
Cindy	S. Carolina	1	0	75,000
Debra	Texas	0	0	7,000,000
Gracie	S. Carolina, Georgia, Virginia	22	0	14,000,000
Irene	Extreme northwestern Florida	0	0	Minor
Judith	Southern Florida	0	0	Minor
Total		24	33	$23,231,000

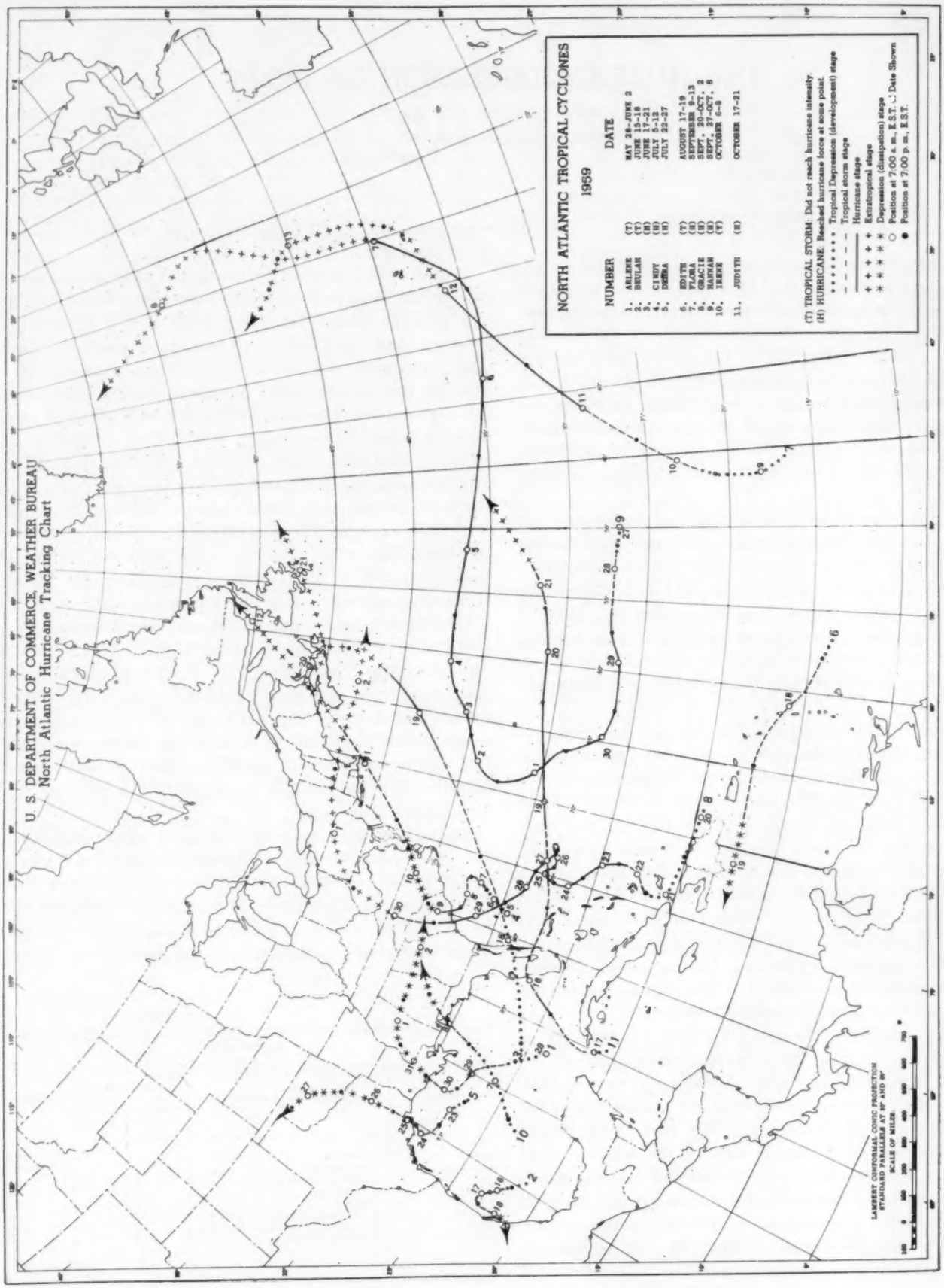
NORTH ATLANTIC TROPICAL CYCLONES
1959
NUMBER
DATE
1. ARLENE (T) MAY 28–JUNE 2
2. BERTHA (T) JUNE 13–18
(H) JUNE 17–21
3. CINDY (H) JULY 5–13
4. DEBRA (H) JULY 22–27
5. EDITH (T) AUGUST 17–19
6. FLORA (H) SEPTEMBER 9–13
7. GRACIE (H) SEPT. 20–OCT. 2
8. HELENE (H) SEPT. 27–OCT. 8
9. IRENE (T) OCTOBER 6–8
10. JUDITH (H) OCTOBER 17–21
(T) TROPICAL STORM. Did not reach hurricane intensity.
(H) HURRICANE. Reached hurricane force at some point.
Tropical Depression (development) stage
Tropical storm stage
Hurricane stage
Extratropical stage
Depression (dissipation) stage
Position at 7:00 a. m., E.S.T. Date Shown
Position at 7:00 p. m., E.S.T.
U. S. DEPARTMENT OF COMMERCE, WEATHER BUREAU
North Atlantic Hurricane Tracking Chart
LAMBERT CONFORMAL CONIC PROJECTION
STANDARD PARALLELS AT 20° AND 60°
SCALE OF MILES

FIGURE 1.—Tracks of North Atlantic tropical cyclones of 1959.

(weaker) than normal between latitudes 25°–30° N. and 45°–50° N. However, the displacement of these anomalies was so far to the north that weakened westerlies were the principal result, but the easterlies were also weaker than usual. The August circulation appeared to approximate more closely the Ballenzweig [3] "favorable" than the "unfavorable" type. In the middle and upper troposphere a trough persisted in the middle Atlantic during much of the month and temperatures at these levels over the area of normal tropical cyclone development were apparently colder than normal.

In September, 700-mb. heights continued below normal over the subtropical portion of the western Atlantic and above normal over the northeastern United States and Canadian Maritime Provinces, resulting in a return to above normal easterly flow over the southern portion of the North Atlantic Ocean. Hurricane activity in September was normal or slightly higher. The trough in the middle Atlantic continued at high latitudes but did not extend as far south as in August.

2. INDIVIDUAL TROPICAL CYCLONES

Arlene, May 28–June 2.—Tropical storm Arlene originated in an easterly wave which was fairly well defined with a northeast-southwest orientation over the Dominican Republic as early as May 23. Shower activity indicating low stability was evident over a wide area including most of the Caribbean Sea and the Bahamas. At 0700 EST on the 25th, a weak cyclonic flow appeared at 500 mb. over the northwestern Caribbean, but there was no evidence of any concentrated bad weather. About this time a slow but definite increase in pressure gradient began north of western Cuba, leaving an extensive area of relatively slight gradient over the western Caribbean Sea. This trend in the pressure pattern continued until wind warnings were required for small craft on both coasts of Florida on May 27. The 500-mb. Low, had moved into the southeastern Gulf of Mexico on May 27 and on the 0700 EST surface chart of May 28 a ship reported a light southwest wind at 22.5° N., 86.5° W., providing the first indication that the closed circulation had extended down to the surface.

Ship reports during the evening of May 28 confirmed the development of tropical storm Arlene and the New Orleans Weather Bureau office at 2100 CST issued the first tropical storm advisory of the 1959 season. The storm center moved northwestward for about 12 hours from its initial position near 26° N., 88° W. Thereafter it moved westward for 12 hours, became stationary at 28° N., 92° W. during the night of May 29–30, and then moved northward across the Louisiana coast between Weeks Island and Pt. Au Fer, La., during the late afternoon of May 30. Winds diminished gradually after the center crossed the coast. The low pressure center later moved northeastward and eastward across northern Alabama and Georgia. This was the earliest storm of record to cross the Louisiana coast.

Highest winds reported in the storm were 48 kt. with gusts to 65 kt. on the Louisiana coast. Lowest central pressure reported was 999.7 mb. at Patterson, La. Several ships and Navy reconnaissance aircraft also reported a central pressure of around 1,000 mb. while the storm was over the Gulf of Mexico. Highest tides were 3 feet above normal at Weeks Island and Pt. Au Fer, La. One man was drowned in the surf at Galveston.

The storm produced locally heavy rains over the southeastern portions of Louisiana and Mississippi. Moisant International Airport (New Orleans) received 11.09 inches in 24 hours and Houma, La., 11.35 inches from 0700 CST May 30 to 1030 CST May 31 and 13.13 inches in three days. Heavy rains associated with Arlene fell from southeastern Louisiana to northern Georgia resulting in some crop damage and serious flooding along some small streams; however, other property damage was slight. Total damage was estimated at approximately $500,000.

Beulah. June 15–18.—Tropical Storm Beulah was first detected during the night of June 15–16 when the SS *Hondo* reported a 50-kt. northeasterly wind with heavy rain and high seas near 23° N., 96° W. The storm was short lived as it drifted northwestward on the 16th, westward during the 17th, and turned southward moving inland over Mexico south of Tampico on the 18th.

Highest winds were estimated by reconnaissance aircraft at 61 kt. with lowest pressure 987 mb. This is consistent with Fletcher's formula [6] for maximum wind based on minimum pressure. The storm weakened rapidly on turning southward late on the 17th, and winds were generally less than 30 kt. as it moved inland. No reports of damage have been received from Mexico; it was probably minor.

The synoptic situation contributing to the formation and dissipation of Beulah was rather complex. Pressure first began to fall over the western Gulf on June 13 with the movement of a weak cold front into the northern Gulf. A rather strong anticyclone centered over the Great Lakes contributed to a marked increase in the easterly flow over the northern Gulf. This High broke down rapidly on the 15th and 16th with the approach of an active short wave from the Plains States, probably one of the factors that prevented Beulah from becoming a well developed storm. At the 500-mb level, a very deep Low was located over the New England States throughout this period with short waves "digging" southeastward into the Mid-Atlantic States. In the upper troposphere, conditions became favorable for development in the western Gulf after a weak trough at 200 mb. in that area began to retrograde causing winds at Corpus Christi and Brownsville to shift from northwest on the 14th to south and southwest on the 15th. This condition was short lived as upper winds again shifted to west and northwest with the approach of an active short wave at middle latitudes on the 17th.

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Unnamed Hurricane, June 17–21.—While Beulah was developing in the southwestern Gulf of Mexico, an unstable easterly wave was noted in the northwestern Caribbean on June 15. This wave moved northwestward into the central Gulf on the 16th and a weak closed circulation appeared in the east-central Gulf on the 17th. It began moving northeastward, while at the same time Beulah in the extreme western Gulf was drifting west and south.

When the tropical depression was still about 350 miles west of Miami, a tornado moved across the city of Miami at about 10 p.m. EST on the 17th, lasting 20–30 minutes and causing approximately $1,500,000 damage, many injuries, but no deaths. At the same time another tornado formed north of West Palm Beach and lasted about 20 minutes but fortunately traversed a sparsely inhabited area. The tropical cyclone moved across central Florida during the night of June 17–18 attended by heavy rains and gusty winds, fluctuating rapidly in the Sarasota-Bradenton area from 9–13 kt. to 43 kt. Tides 2½ to 3 feet above normal were reported along the beaches from St. Petersburg to Naples causing damage estimated at $156,000. The torrential rains following previous heavy rainfall caused considerable additional damage to crops, particularly in the Fort Myers area.

Several bulletins on this storm were issued by the Miami Hurricane Center. The last, on the afternoon of June 18, indicated winds of 43 to 56 kt., and the likelihood of additional development, and contained cautionary advices to shipping.

After passing off the Florida east coast the storm deepened steadily and at 0250 GMT on the 19th, the *Atlantic Union* reported a barometer reading of 993 mb., falling, and west-southwesterly winds occasionally 80 kt. Although the hurricane was in a diffused frontal zone, it now appears to have remained warm-core and essentially tropical for some time. The lowest reported pressure was 974 mb. The hurricane struck the Canadian Maritime Provinces in the vicinity of Northumberland Straits. Associated wind and barometric data as the storm moved inland are lacking, but the press reported 33 deaths, mostly lobster fishermen, and considerable property damage. Notices of this severe storm had been carried in the NSS bulletins.

Cindy, July 5–12.—The fourth tropical cyclone of the season, Cindy, barely reached hurricane force before it crossed the coastline north of Charleston, S.C., on July 8. The circulation which produced the storm had been noticed first some three days earlier off the Florida upper east coast. A deepening low pressure system had moved from the Great Lakes to the Canadian Maritime Provinces while the associated cold front moved southeastward and became stationary from near Bermuda to extreme northern Florida. With the fracture of the short-wave trough, a cut-off Low developed off the south Atlantic coast—most pronounced at the 500-mb. level. Usually tropical storms forming in this type of situation develop slowly, remain small, and seldom intensify to much more than minimal hurricane strength. Cindy conformed to this pattern.

On July 6, winds just east of the center increased to 26–35 kt. as convective activity, evidenced by numerous showers extending outward some 200 miles to the north, contributed to the conversion from a cold to a warm-core system. An intensifying anticyclone increased the easterly gradient north of the center and Cindy developed and intensified. A reconnaissance plane located the eye late on the afternoon of the 7th some 190 miles east of Charleston with maximum winds 52 to 56 kt. and minimum pressure 997 mb. The small storm moved northwestward, reaching hurricane intensity a short distance offshore, and the center made landfall about 0245 GMT on the 9th between Charleston and Georgetown, S.C. Winds of 56 kt. were recorded at McClellanville, a short distance inland, with squalls estimated at just about hurricane force in the sparsely settled coastal area. The storm tide was about 4 feet above normal near the center.

The storm curved northward through South Carolina on the 9th and then turned northeastward at a little faster rate to the southern tip of Chesapeake Bay by late afternoon on July 10. The sustained winds had dropped rapidly after the center moved inland but gusts up to 39 kt. were still occurring at this time. As the remains of the circulation moved back into the Atlantic, marked re-intensification took place. At 0600 GMT, with the center some 75–100 miles off the New Jersey coast, the ship *Ocean Monarch* reported winds of 65 kt. just southeast of the center, and other ships reported 45 to 50 kt. Accelerating northeastward, Cindy had passed across Cape Cod by 1200 GMT July 11. Winds were generally 22 to 35 kt. along the coast but ranged up to 35 to 52 kt. over the open waters just east of the center with a gust of 59 kt. at Block Island, R.I.

The intimate association of tropical storm behavior with features in the westerlies is well illustrated by Cindy. Three successive short waves played important roles. The passage of the first of these across the northeastern United States was followed by the development of the cut-off Low in which Cindy formed. The increase to storm intensity occurred as the next trough passed and the storm was then deflected abruptly to the west by the following anticyclone. Finally, the intensification on moving back to sea can probably be related in part to the passage of the third short wave in the series across the northeastern United States at that time. Some re-intensification often occurs when a tropical storm moves from land to sea but the marked deepening of Cindy was more than would normally be expected after allowing for decreased surface friction and increased moisture supply but relatively low water surface temperatures. However, it is significant that, coincidental with the movement of Cindy off the coast, a short wave passed to the north with a strong jet maximum (120 kt.

or higher at 200 mb.) moving through New England. The divergence pattern associated with this jet was such as to favor high-level outflow from the storm, contributing to re-intensification.

While Cindy was not typical of storms which develop in deep easterlies south of the subtropical ridge, its behavior does emphasize the necessity of recognizing and anticipating the effects of patterns in the westerlies on tropical cyclones.

Since Cindy was small, of minimal hurricane intensity, and did not strike a thickly populated area, property damage was relatively minor. The only casualty reported was a man killed near McClellanville, S.C., when his automobile collided with a fallen tree. Wind damaged some roofs and blew down trees and power lines in South Carolina and some damage to buildings resulted from several small tornadoes attending the storm in northeastern North Carolina and southeastern Virginia. Heavy rains occurred along and near the storm path through South Carolina, North Carolina, southeastern Virginia, and the immediate coastal areas northward to Maine. The largest precipitation amounts were in South Carolina with 6 to 8 inches general through central portions of the State and unofficial but reliable reports of up to 15 inches near Columbia. Local flooding of lowlands resulted but no major flood situations developed and the rains in the Carolinas were largely beneficial as they relieved a drought situation.

Debra, July 22–27.—The beginning of hurricane Debra can probably be traced back to July 15. Considerable shower and thundershower activity began about this time in the western Bahamas and over Florida, under the influence of a cold-core vortex which developed in the high troposphere and at 500 mb. drifted slowly southwestward through the western Bahamas, over western Cuba, and into the east Gulf of Mexico by the 20th. The activity spread into the Gulf as the upper circulation flattened into an inverted trough and continued westward.

The first weak surface circulation, detected as early as 1900 EST on the 20th, later developed into hurricane Debra over the northwestern Gulf of Mexico. The circulation continued weak until the 23d, when winds up to 22–30 kt. accompanied showers and squalls in the northwestern Gulf and along the Louisiana and upper Texas coasts.

An indication that some intense weather was in the making in the western Gulf of Mexico came from the SS *Atlantic Navigator* (at 0000 GMT on the 24th at 23.7° N., 94.5° W.) which reported a northwest wind of 32 kt. with rough seas from the southwest. This was later corrected to southwest wind of 23 kt. The report indicated that a vortex was developing, which was later verified by reports from that area and to the north toward the Texas coast during the next 12 to 18 hours.

A delayed observation, received at 1130 GMT on the 24th from the ship *Mexican Trader* (located at 28.0° N., 94.2° W.) reporting a surface wind from the southwest at 40 kt. and pressure of 1007.5 mb., indicated additional intensification. At 1200 GMT this ship had moved about 60 miles west and the surface winds had increased to southwest 50 kt. That Debra was already a fully developed hurricane is evidenced by the radar photograph (fig. 2) taken at the Dow Chemical Plant in Freeport at 0733 CST July 24 when the set was turned on. No spiral organization had been noted on the radar scope the previous afternoon.

Reconnaissance aircraft located the center of tropical storm Debra during the early forenoon of July 24. It seems likely the plane did not pass through the most severe squalls prevailing at the time.

Hurricane Debra increased further in intensity during the afternoon and evening of July 24 and passed inland on the Texas coast between Freeport and Galveston near midnight on the 24th. It continued slowly northward across extreme eastern Texas and rapidly lost intensity on the 25th and 26th, and finally lost its identity in central Oklahoma on the 27th.

The subtropical ridge, surface and aloft, was fairly well established over the Atlantic and westward across the Gulf States, while the easterly wave in which Debra was spawned moved from the Bahamas across the Florida Straits and the Gulf of Mexico. At about the time that Debra intensified and became a hurricane, a polar trough moved eastward into the central portion of the United States. This was responsible for the southerly shift of winds at 500 mb. and above that steered Debra northward instead of west-northwestward or northwestward which seemed indicated earlier.

The lowest reported central pressure in hurricane Debra was 984.4 mb. from the Coast Guard Cutter *Cahoone* late on July 24. Dickinson, Tex. reported 986.5 mb., the lowest reading from a land station. Highest reported wind was 70 to 78 kt. with gusts to 91 kt. from Brazos Floodgates near Freeport, Tex. Tides were generally 3 to 5 feet above normal over Galveston Bay. Morgan Point, at the head, or north, end of Galveston Bay, reported the highest tide of 7.9 feet m.s.l. Rainfall was heavy throughout eastern Texas and extreme western Louisiana; Orange, Tex., reported the greatest amount, 14.42 inches.

No casualties occurred in connection with Debra, but ten persons suffered minor injuries in Brazoria County, Tex. Damage in Brazoria, Galveston, and the eastern portion of Harris County, Tex., was estimated at $6,685,000 with some additional in other areas.

Development so close to the coastline is rather unusual and the forecast problem was complicated by lack of ship reports, and delays and transmission errors in the few that were received.

Edith, August 17–19.—Tropical storm Edith formed in an easterly wave in the Atlantic Ocean east of the Windward Islands. At 1530 EST, August 17, reconnaissance aircraft found a weak center near 13.8° N., 57.2° W. The minimum surface pressure was 1007 mb., while highest winds were 30 kt. in squalls north of the center. The

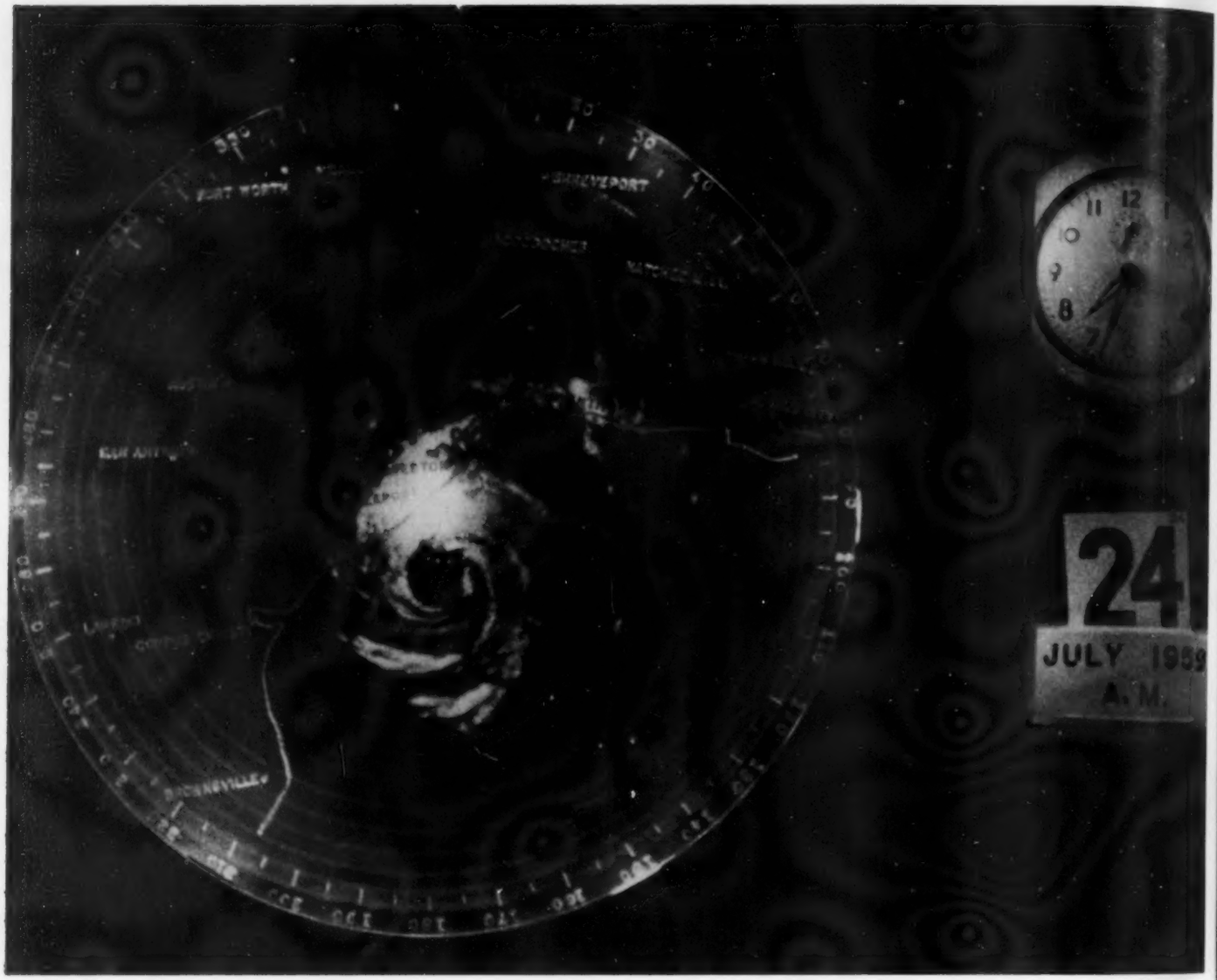

FIGURE 2.—Radar picture of hurricane Debra taken when the hurricane was just off the coast. (Courtesy Roy C. Jorgensen, Dow Chemical Company, Freeport, Tex.)

storm was never well defined as it moved on a west-northwestward course with an average speed of 20 kt., passing through the Leeward Islands in the vicinity of Guadeloupe early on the 18th. Highest winds never exceeded 48 kt. and the storm dissipated just to the south of Mona Passage during the night of August 18–19. Indeed, there is considerable doubt if a complete circulation ever existed and whether this disturbance meets the specifications for a tropical storm.

There were two important synoptic features associated with this storm. Very warm air was observed in the middle troposphere just prior to formation, and the wind field in the high troposphere never became favorable for high-level evacuation.

There were no reports of loss of life or of damage attributable to Edith.

Flora, September 9–13.—The history of the formation of Flora is rather uncertain beyond about 24 hours prior to the first advisory issued at noon EST, September 10. However, four days earlier, on the afternoon of September 6, pressure and wind in the Cape Verde Islands indicated a trough passage. This trough could not be followed from day to day through the ocean area due to a lack of reports, but if it moved at an average speed of 13 kt. it would have reached the position where Flora was found on September 10 near latitude 22.1° N., longitude 46.3° W. Ship and aircraft reports indicated highest winds of 39 kt. and minimum central pressure of 1008.1 mb. Succeeding positions of the storm center indicated that it was already on a northerly course and it continued to curve through northeastward to east-northeastward, crossing the southernmost islands of the Azores group late on September

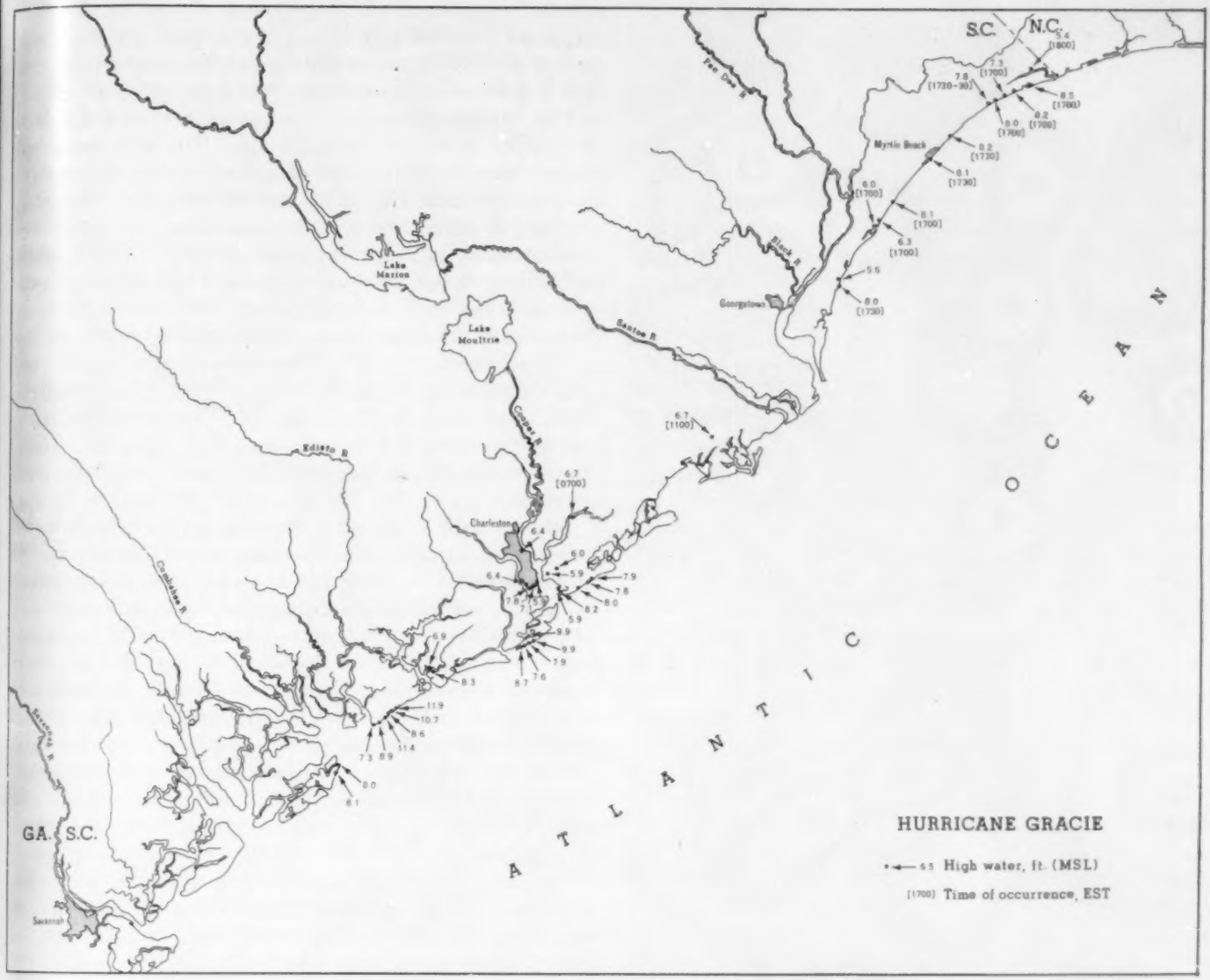

FIGURE 3.—High water (ft., m.s.l.) recorded during hurricane Gracie, September 1959.

12. Later the same day reconnaissance aircraft found no evidence of a tropical storm as it combined with a cold front and moved into a large polar Low.

By mid-morning of September 11, aircraft found that Flora's winds had increased to barely hurricane force, 65 kt., and the minimum pressure was 994 mb. The next highest wind speed reported was 60 kt. on the afternoon of the same day when central pressure had risen to 1001.0 mb. On September 12, although a lower pressure of 994.2 mb. was measured as the storm became extratropical, highest surface winds were about 45 kt.

Flora recurved quickly to the north and northeastward before she became a threat to any land areas except the Azores islands, due to a major trough in the westerlies extending southward into the Tropics. No loss of life or property damage has been attributed to Flora.

Gracie, September 20–October 2.—Gracie, a major hurricane, was one of the most troublesome storms of the 1959 season to forecast. The easterly wave in which it formed had been followed for some 5 days and its sudden development and intensification is difficult to explain. Gracie's erratic movement between the 22d and the 27th, when at one time or another it moved in about every direction of the compass (see fig. 1), proved impossible to forecast in detail. The winds in the southwestern Atlantic during this period at all levels were extremely light and variable and there was no well defined steering current. The storm began moving slowly but steadily toward the west-northwest on the 27th and continued toward the west-northwest and northwest, passing inland on the South Carolina coast near Beaufort around noon on the 29th.

The easterly wave in which Gracie developed was first

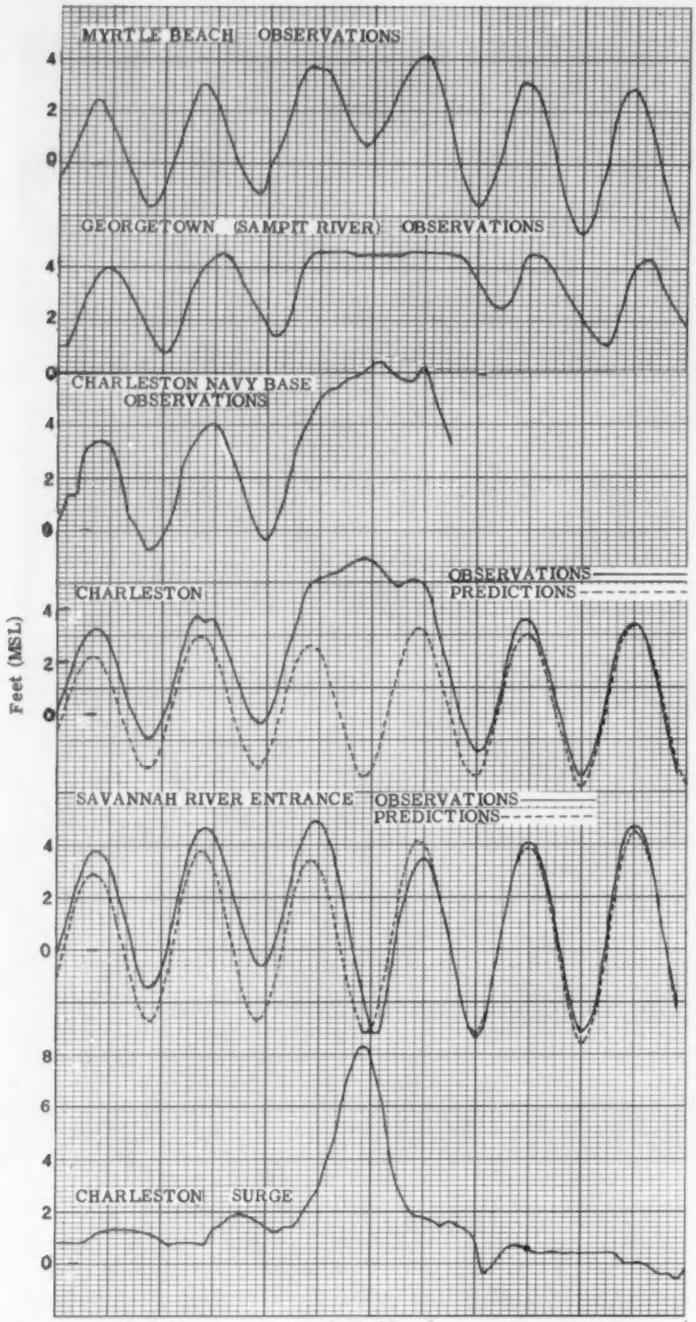

FIGURE 4.—Observed and predicted tides along the South Carolina coast preceding, during, and following hurricane Gracie, September 1959.

noted on September 16 about midway between the Lesser Antilles and Africa. It moved westward at about 17 kt. during the next 5 days eventually moving into the southeastern Bahamas. The wave was investigated daily by reconnaissance aircraft beginning on the 18th and no closed circulation was found until the 22d. Indeed, the wave remained remarkably constant in all details and was attended by heavy shower activity from the time first noted. The island of Mayaguana in the southeastern Bahamas reported 8.40 inches of rain during the 12-hour period from 1900 EST on the 21st to 0700 EST on the 22d. The hurricane was quite wet throughout its history.

The surface pressure pattern over the Atlantic from September 16–29 was about normal. The most important feature was the movement of a strong polar anticyclone from the northern United States into the western Atlantic, resulting in strong anticyclogenesis and an increase in low-level easterlies in the southwestern Atlantic. The initially cold High was gradually transformed into a warm anticyclone which extended well into the middle troposphere. However, weak short waves in the polar westerlies to the north of the hurricane shortly weakened the high and resulted in a very weak steering current. Not until the 27th, when rising heights in the middle troposphere north and northwest of Bermuda increased the easterly current, did hurricane Gracie develop a relatively straightforward movement.

At 200 mb. a moderately strong high pressure cell existed about over and to the east and northeast of Gracie during September 22–24, but as Gracie drifted northward the High eventually became located south and southeast of the hurricane by the 25th and 26th. During this whole period the circulation in the upper troposphere was very complex and contained many small-scale cyclonic and anticyclonic eddies. On the 28th and 29th the overall anticyclonic flow had simplified greatly and the center of the upper level High again became located north and northeast of Gracie resulting in a rather uniform steering current from the east-southeast throughout the entire troposphere.

The intensity of hurricane Gracie was as erratic as its movement. On September 22 the storm deepened rather rapidly to 997 mb. with winds 78 to 87 kt. On the 23d and 24th, central pressure varied from 1000 to 1006 mb. with winds from 45 to 65 kt. On the 25th the minimum barometer again dropped to 997 mb. and reconnaissance aircraft reported an increase in maximum winds, the size of the storm area, and the intensity of weather around the eye. On the 27th the central pressure decreased further to 979 mb. with an almost complete wall cloud. The hurricane continued to intensify further during the next 2 days to 950 mb.

The center of the hurricane crossed the coast near Beaufort, S.C., near noon on September 29. The Marine Corps Auxiliary Air Station at Beaufort reported a minimum barometer reading of 950 mb., a sustained 5-minute wind of 84 kt., and gusts estimated to 120 kt. Wind was estimated as high as 152 kt. closer to the exact center of the storm and gusts as high as 130 kt. seem quite credible. After moving inland the hurricane weakened gradually as it turned northward along the Appalachians.

Rainfall of 3 to 8 inches occurred in South Carolina and portions of Georgia, while in North Carolina 2 to 4 inches were reported with local amounts up to 8 to 10 inches.

Some flooding occurred, particularly in the Carolinas and Virginia and crop damage, due to wind and rain, was heavy in South Carolina and eastern Georgia. The rainfall was generally beneficial in most sections from North Carolina northward ameliorating near drought conditions in many areas.

A series of tornadoes attended the passage of the dying storm through Virginia and 12 persons were killed in one tornado at Ivy near Charlottesville. Ten others lost their lives in South Carolina and Georgia, mainly due to automobile accidents, falling trees, and live wires. Wind damage was severe near the eye in the coastal area as Gracie moved inland and was described as the most severe in the history of Beaufort, S.C. Damage has been estimated at $14,000,000, about half occurring in Charleston County, S.C.

Accurate detailed prediction of the extremely erratic course of this hurricane during its early stages was beyond the capability of the science at this time. After the steering current simplified early on the 27th, forecasts and warnings issued in connection with Gracie were exceptionally accurate. A hurricane watch was announced for the area from Savannah, Ga. to Wilmington, N.C., at 1100 EST, September 28, and hurricane warnings were issued at 1400 EST on the 28th for the area from Savannah to Wilmington. As a result of the accurate warnings, evacuation from vulnerable islands and beaches was almost total. Effective community action on the basis of these warnings and the landfall of Gracie near the time of normal low tide were responsible for the low loss of life. Indeed, there were no known fatalities from hurricane tides and waves. The maximum tide was about 9 to 12 feet m.s.l. [7], (see fig. 3).

Figure 4 shows the continuous tide record at Charleston, S.C. It can be seen that the peak difference coincided within an hour with low tide. The high water marks in figure 3 would undoubtedly have been much higher if the storm center had reached the coast either a few hours earlier or later than it actually did.

Hannah, September 27–October 8.—On September 27, when hurricane Gracie was some 300 miles off the Florida east coast, ship reports indicated the development of a broad cyclonic circulation centered in the Atlantic near latitude 27° N., longitude 50° W. Aircraft reconnaissance the next day found a fully developed hurricane circulation and the first advisory on Hannah was issued at 2300 GMT, September 28. The hurricane at this time was located near 27° N., 57° W. and was moving toward the west at about 14 kt. with highest winds around 74 kt.

Hannah increased in intensity during the next 48 hours with central pressure dropping to 959 mb. and maximum winds reaching 108 kt. Minimum pressure and intensity remained about the same during the next three days as the storm curved northward about 200 miles west of Bermuda and then accelerated to about 17 kt. toward the east on October 4. The last advisory was issued when the hurricane was 200 miles south-southwest of the Azores on October 6. Winds near the center at this time were still estimated at 87 kt. Details of later stages are lacking but indications are that a gradual decrease in intensity then began as the storm moved northeastward, merging with an intense cyclone centered southeast of Greenland.

Upper air data in the area traversed by Hannah are too sparse to permit a comprehensive study of factors associated with its development. The 500- and 200-mb. charts indicate that the initial circulation formed under the eastern side of a progressive upper trough extending southward from the southern tip of Greenland. As the northern portion of the trough continued eastward and the developing hurricane moved westward, it passed to the south of a strong 500-mb. anticyclone, the same High which was associated with hurricane Gracie, and this was the period of maximum intensity of Hannah. Eastward motion of this High permitted first Gracie and later Hannah to recurve.

Hurricane Hannah never became a serious threat to the United States coast, or to Bermuda, and it presented no particularly difficult forecast problems. The most unusual feature of the storm was its long life and sustained intensity, somewhat similar to hurricane Carrie of 1957. A hurricane beacon developed cooperatively by the Air Force Geophysics Research Directorate and the Weather Bureau was tested in the hurricane on October 1–4. Some highly encouraging results were obtained since the beacon balloon remained in and transmitted signals from the eye for 24 hours on one occasion.

Irene, October 6–8.—Tropical storm Irene formed on October 6 in the central portion of the Gulf of Mexico and moved north-northeastward during the next two days. The lowest sea level pressure reported by reconnaissance aircraft was 1001 mb. The highest winds were gusts of 48 kt. in squalls at the Pensacola Airport. Irene was never a well organized storm and although the center moved inland near Pensacola early on the 8th, highest tides were 4.4 feet above normal at Cedar Keys, Fla., a considerable distance east of the track and landfall.

Prior to the development of Irene, a short wave with surface cyclogenesis moved through the southern Plains and Texas on October 4. This permitted the trailing cold front to move into the western Gulf of Mexico on the 5th; the front then dissipated leaving a rather sharp trough. At 500 mb., temperatures over the western Gulf were relatively warm. At 200 mb., a weak anticyclone persisted over the surface development.

No deaths were reported and damage was not significant.

Judith, October 17–21.—Activity along the intertropical convergence zone continued strong throughout mid-October in the Caribbean and Central America area. Pilots reported 52-kt. squalls in the vicinity of 15° N., 73° W., late on the 10th and early on the 11th, but the perturbation continued along the ITC with no development. During the afternoon of the 11th a new unstable easterly wave approached the Leeward Islands, and Barbados experienced heavy squalls. This wave moved steadily across

the Caribbean at 15 kt. and on October 15 developed a weak circulation south of Jamaica. During this same period, a tropical low pressure pattern gradually developed in the Bay of Campeche, remaining essentially stationary, while a cold front moved slowly southeastward from Texas into the western Gulf of Mexico.

On the morning of October 16, the Caribbean wave had drifted into the Gulf of Honduras, the Campeche depression had weakened, and the west Gulf front had become diffused. Squalliness had decreased although moderate squalls were still occurring as far east as Jamaica. The Caribbean wave had been investigated daily by aircraft reconnaissance and, since development was thought possible when the two disturbances eventually merged in the south-central Gulf, arrangements were made for aircraft reconnaissance in the area the following day.

At both 1300 EST and 1900 EST on the 16th, all reporting stations within 500 miles of the disturbed area reported 24-hour rises in surface pressure. However, surface reports at 0700 EST on the 17th, as well as aircraft reconnaissance during the forenoon, indicated a complete circulation. Gale warnings were issued for the Florida Gulf coast south of Cedar Keys at 1600 EST as gradual intensification occurred during the day.

In the afternoon, shortly before departing for home base, the aircraft reported a new center apparently developing some 150 miles northeast of the old center, with 45-kt. surface winds. At 1700 EST, the MV *Italsole* encountered a small vortex at 24.5° N., 83.7° W. with the barometer falling rapidly from 1008.5 to 999.3 mb., and the wind increasing to 43 kt. The wind shifted gradually from east-southeast to southwest in 30 minutes. The barometer then began rising steadily. An hour or two later another ship in the same area reported winds of hurricane force. With fairly rapid intensification indicated by these ships and by aircraft and with direction of movement in doubt, hurricane warnings were issued at 2030 EST for the Florida Gulf coast from Punta Gorda to Cedar Keys.

The observer at Dry Tortugas, some 70 miles west of Key West, reports as follows:

> Late in the afternoon, Cuban fishing boats in the area came to Dry Tortugas harbor area to avoid rough water. Just before dark the wind began to pick up, and in about 5 minutes the wind increased from about 10 m.p.h. to about 50 m.p.h. and the ocean became extremely rough. The high winds (about 50–55 m.p.h.) continued, developing waves of nearly 10 feet. The wind shifted from east to south and blew all night at about 50–55 m.p.h., although the rain did not get above a heavy drizzle.

Neither the Miami WBO radar (the new WSR–57) nor the reconnaissance aircraft radar could pick up any wall cloud around the eye during the night and thus it was difficult to track the storm center. With time, the weather bands observed on radar appeared to lose intensity as well as much of their spiral character. These radar observations and weather trends along the Florida Gulf coast indicated definite loss of intensity and hurricane warnings were changed to gale warnings at 0500 EST.

The storm center reached the coast near Boca Grande Island between 0800 and 0900 EST on the 18th, with lowest pressure 999.0 mb., and very little wind north of the center. South of the center the maximum sustained velocity at Fort Myers was south-southwest 35 kt., and gusts to 46 kt. Total rainfall was 7.57 inches and highest tides 2½ feet above normal. There were no deaths but one injury.

The storm crossed the Florida peninsula during the 18th, passing into the Atlantic near Fort Pierce. Gales were reported over extreme southern Florida with gusts of 48 kt. at Miami. Within a few hours after the storm passed out to sea, a new center apparently developed just northeast of Great Abaco Island in the Bahamas and began to intensify, reaching hurricane force by the next morning. Again the strongest winds first appeared on the south side of the center but gradually extended completely around the storm.

During the period of tropical storm and hurricane intensity, Judith moved in good agreement with the 500-mb. steering. In the high troposphere (200 mb.) winds were westerly in a relatively cold trough as the wave moved across the eastern and central Caribbean and no intensification occurred. The trough narrowed and began to fracture during the night of the 14th and a high pressure pattern developed over the eastern Caribbean. As the wave passed under a band of southerly winds between the trough and the High some intensification took place, which ended as the surface Low passed under the high-troposphere Low. Redevelopment began as the surface disturbance passed under the high-level ridge in the extreme southeastern Gulf. No explanation is available for Judith's loss of intensity in the 6- to 8-hour period prior to landfall on the Florida west coast. Re-intensification over the Atlantic took place under west-southwesterly winds of around 45 kt. at 200 mb.

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Weather Note

UNUSUAL WAVE CLOUD OVER WASHINGTON, D. C., NOVEMBER 30, 1959

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The striking and spectacular wave cloud formation shown in the accompanying photograph (fig. 1) appeared over Washington, D.C., on November 30, 1959. These clouds persisted from about 1100 to 1500 EST. There were several pilot reports of turbulence and downdrafts over the general area during this period.

The base of the clouds was estimated at between 10,000 and 12,000 feet above sea level. The orientation of the long bands was from about 230° extending toward 50°. The long wave bands were estimated by pilots to be between 4 and 5 miles apart. Pilots reported that the wave bands extended all the way back to the mountains west of Washington. At least nine separate wave bands can be observed in the photograph. These clouds were nearly stationary except for a slight drift of the entire cloud system downwind.

An inspection of the morning sounding taken at Washington, D.C. (fig. 2), shows a nearly adiabatic layer from 680 to 620 mb. and a layer above the 600-mb. level with a lapse rate of about 0.7 the dry adiabatic rate. These layers are separated by a stable layer with a 1° C. inversion between 620 and 600 mb. The winds were from about 310° and the speeds were about 40 knots (20 m. sec.$^{-1}$) in the lower layer and 65 knots (33 m. sec.$^{-1}$) in the upper layer. The sounding shows very dry air from 5,000 to nearly 10,000 feet.

Unfortunately, there is no radiosonde report for 1300 EST. However, the 1300 EST upper-level winds showed little change from the 0700 EST winds, and it is assumed that the temperature at 1300 EST was similar to that at 0700 EST. Using a mean temperature lapse rate of 0.8 times the dry adiabatic for the two layers, with a 1° A. temperature inversion between the layers, a mean temperature of 255° A., and a wind speed difference across the boundary of 13 m. sec.$^{-1}$, in the equations developed by Haurwitz [1, 2] for billow clouds gives a wavelength of 4.5 km. (2.8 mi.). If it is assumed that the lapse rate steepened slightly during the morning to a temperature lapse rate of about 0.9 times the dry adiabatic, the computed wavelength becomes 6 km. (4 mi.). These results appear to be in reasonable agreement with the observed data.

Work on wave clouds by Colson [3], indicates the need for the presence of a strong wind shear and a stable layer. The main axis of the jet stream in this case appears to have been just to the south, giving strong winds and wind shear over the Washington area. There was a definite stable layer near the 12,000-ft. level (fig. 2).

FIGURE 1.—The series of wave clouds over the Washington, D.C., area on November 30, 1959. Photograph is a composite of a series of photographs taken by E. Orr, U.S. Weather Bureau, from the roof of the Weather Bureau building at 24th and M Streets N.W. in Washington. The view is from the west through north to east (left to right).

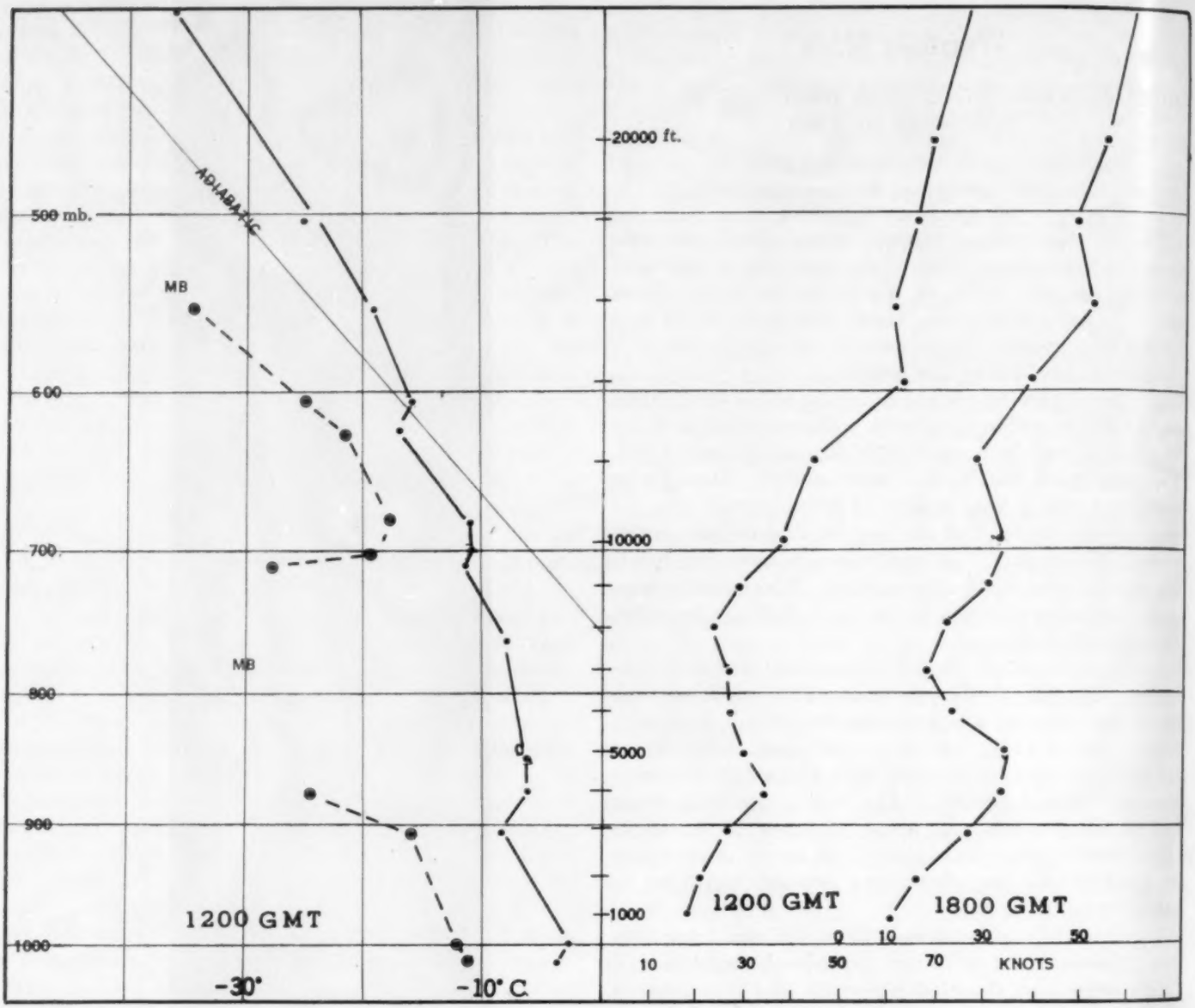

FIGURE 2.—Washington, D.C., November 30, 1959. Upper-air sounding for 1200 GMT and winds for 1200 and 1800 GMT.

Work by Scorer [4] shows the importance of the stability term $l^2=g\beta/U^2$ in the establishment of waves, where β is the static stability and U is the wind speed. According to Scorer, the value of the quantity l^2 should decrease in the upper layer over that in the lower layer. In this case, l^2 showed a value of between 2 and 4 below 12,000 ft. and from 0.1 to 0.3 above that level.

During this period, the barograph showed a decrease in pressure between 1000 and 1400 EST which was in excess of the normal diurnal fall. A study of the high-speed barograph trace for this date showed a series of about five separate decreases in pressure between these hours. This would correspond to a drift of about 4–5 m.p.h. of the entire wave pattern.

During the latter part of the afternoon, the cloud pattern dissipated and became quite indistinct by evening. The evening radiosonde report showed a definite increase in moisture in the intermediate layers. There was still a broad inversion of about 2° A. between 5,000 and 6,000 feet. The wind speed difference was from 10 m. sec.$^{-1}$ below the broad inversion to 20 m. sec.$^{-1}$ above it.

Work is continuing on the occurrence of wave clouds over the general Washington area for the entire winter season.

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THE WEATHER AND CIRCULATION OF DECEMBER 1959

An Abrupt Change From A Cold Fall Season

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1. INTRODUCTION

At the close of November 1959, a warm, maritime regime became established over most of North America and persisted throughout December with only minor variations. The pattern of mild temperatures which ensued contrasted sharply with the unseasonable cold of November and, indeed, came close to being the exact opposite. Thus the cool regime which characterized the fall season as a whole [1] terminated abruptly as winter approached.

The mean trough in the 700-mb. contours for the month of December (fig. 1) extended diagonally from Newfoundland across the contiguous United States into lower California. A number of storms, some of which reached blizzard proportions, developed over the Southwest and moved east-northeastward in association with the trough. The result was a wet and snowy month over much of the nation's mid-section.

2. THE MEAN MONTHLY CIRCULATION

One of the most noteworthy aspects of the mean monthly circulation pattern for December (fig. 1) was the marked strength of the zonal westerlies over the oceans as compared to the very weak flow over the continents. Over both the Atlantic and the Pacific, mean wind speeds in the jet stream at 700 mb. exceeded 20 m.p.s. in isotach centers (fig. 2). These speeds were as much as 6 m.p.s. above normal in the Pacific and 10 m.p.s. in the Atlantic. As these currents approached western coasts, however, both underwent marked difluence. For example, the separation between the 9,200-ft. and 10,200-ft. contours expanded from roughly 20° of latitude over oceanic areas to 40° over the continents. On the other hand, flow along or off eastern coasts was subjected to equally marked confluence, so that gradients became restored over the oceans. As far as the Western Hemisphere was concerned, the strength of the maritime westerlies more than balanced the subnormal continental flow, and the resultant mean zonal index for the month over the Western Hemisphere was 1.9 m.p.s. above normal.

CHANGE IN MEAN CIRCULATION FROM NOVEMBER

The largest changes in 700-mb. height departure from normal from November [2] to December 1959, occurred over the Western Hemisphere (fig. 3). The pattern of anomalous change—a large rise center over Canada, another over the central Pacific, and a region of falls in between—was adequate to completely alter the phase of the circulation. Thus, the deep troughs of large amplitude which dominated the central Pacific and North American regions during November gave way to ridges, and a second trough developed in the eastern Pacific southward from the Gulf of Alaska. Such a fundamental shift in circulation is not the usual case from November to December. In fact, an earlier study by Namias [3] indicated that flow patterns between these two months are more likely to be similar than different.

It was over North America, however, that the reversal of pattern was most dramatic in both circulation and weather. As a result of the extensive area over which heights increased (fig. 3) a broad, flat, westerly flow ensued which introduced mild prevailingly maritime air to almost all of Canada and the United States. Mean thickness values for December of the layer 1,000 to 700 mb. (not shown) were well above normal over almost the whole of North America, ranging as high as +330 ft. in central Canada. This change in circulation evolved as a blocking surge retrograded from its November seat over northern Scandinavia (hence the height falls in that area in fig. 3) to the Canadian region early in December. Thereafter the general pattern proved remarkably stable, and it was not until the closing days of the month, when the blocking finally retrograded to the Gulf of Alaska, that the pattern changed and cold continental air was successful in invading the contiguous United States.

Changes from November to December in the Atlantic, while less pronounced than over North America, were in the direction of increasing the westerly flow and deepening the European trough. Thus the geometry of the November pattern was roughly maintained, but with greatly intensified circulation. Under the steering influence of this flow, numerous severe storms crossed the Atlantic

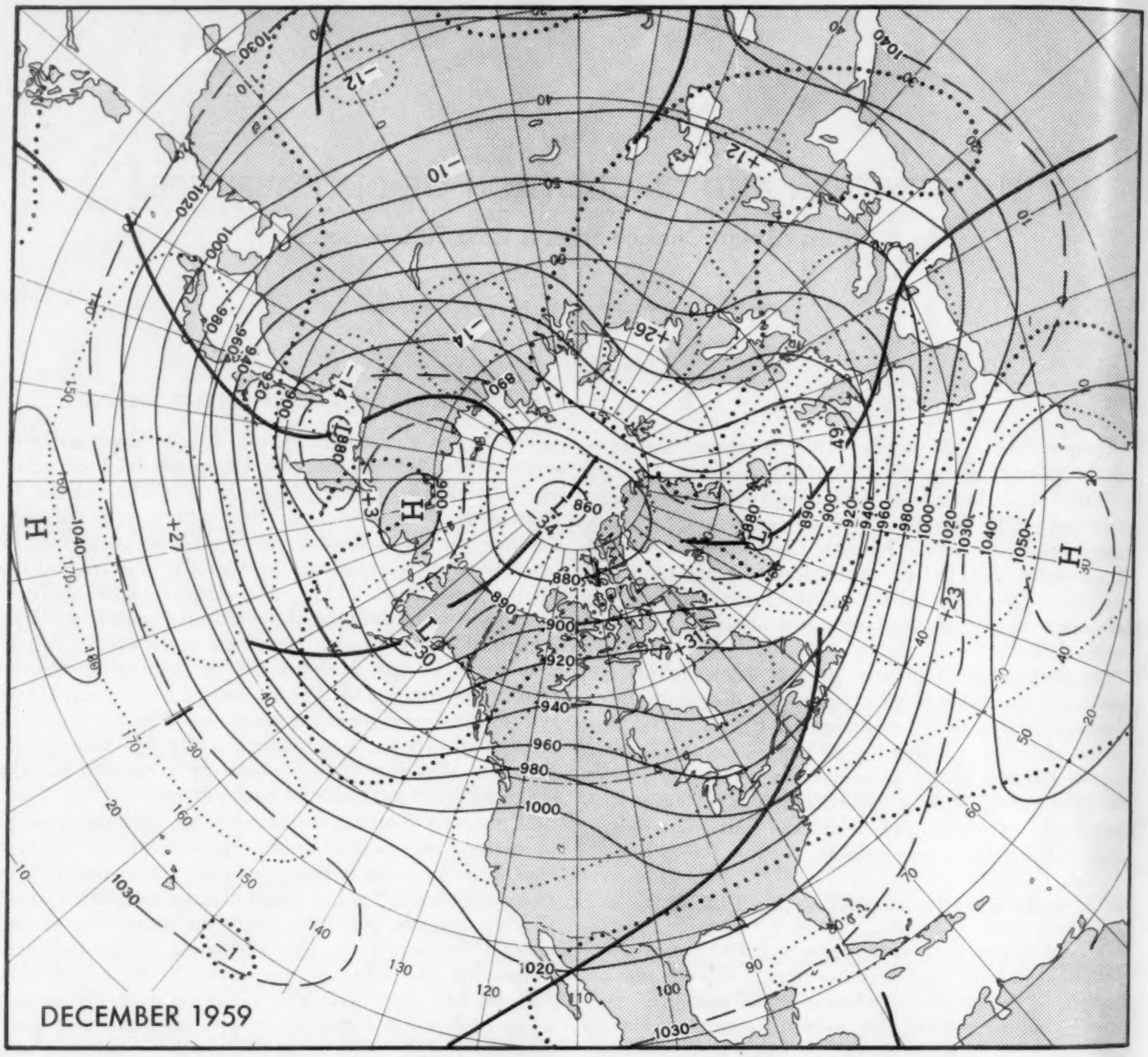

FIGURE 1.—Mean 700-mb. contours (solid) and height departures from normal (dotted), both in tens of feet, for December 1959. Troughs are indicated by heavy lines. Zonal flow was unusually strong over the oceans and weak over the continents. The circulation over the United States was mainly zonal but difluent in the West and confluent in the East, leading to a warm but wet month over much of the country.

and plunged southeastward across Europe and into the Mediterranean. In this manner the British Isles and all of western and southern Europe suffered a period of intense, persistent storminess.

TEMPERATURE

As mentioned previously, the configuration of the mean monthly 700-mb. chart (fig. 1) favored the advection of mild maritime air into the United States and Canada. As a consequence, except for the extreme Southeast and the Great Basin, above normal temperatures prevailed over the entire country, with departures as much as 12° F. in the northern Plains (fig. 4). This pattern stood in sharp contrast, not only to that of the previous month, but also to that of the fall season as a whole. Both these periods were predominantly cold, with the coldest air relative to normal centered in the northern Plains, precisely where December was the warmest.

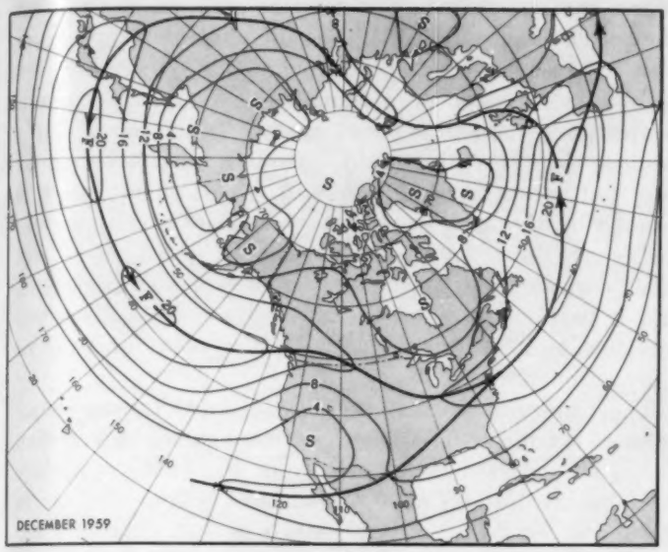

FIGURE 2.—Mean isotachs (in meters per second) of 700-mb. wind speed during December 1959. Solid arrows indicate axes of maximum wind speed. The zonal westerlies were much stronger and better organized over the oceans than over the continents, where there was a tendency to split into two branches.

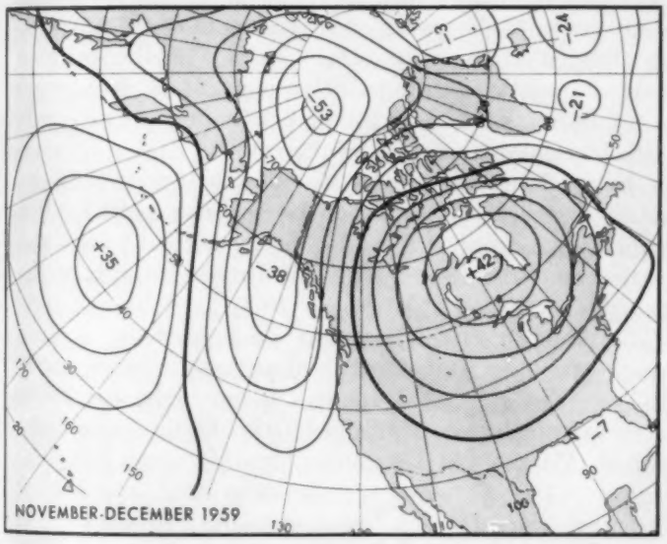

FIGURE 3.—Difference (in tens of feet) between the mean monthly 700-mb. height departures from normal of November and December 1959. Greatest changes took place over the Arctic Basin where heights dropped as much as 530 ft. At middle latitudes, the large rises over Canada and the central Pacific and the falls between completely reversed the circulation pattern of November in the Western Hemisphere.

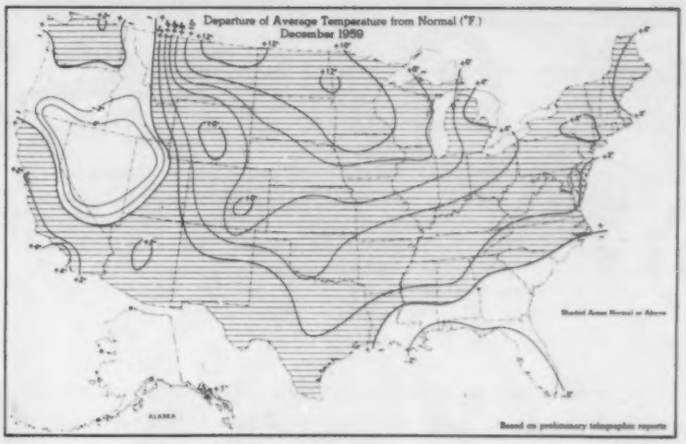

FIGURE 4.—Departure of average temperature (° F.) from normal for December 1959. Hatching indicates areas of normal or above normal temperatures. Unusually mild weather prevailed over most of the United States, with below normal temperatures confined to the Great Basin and the extreme Southeast. (From *Weekly Weather and Crop Bulletin, National Summary*, vol. XLVII, No. 1,Jan. 4, 1960.)

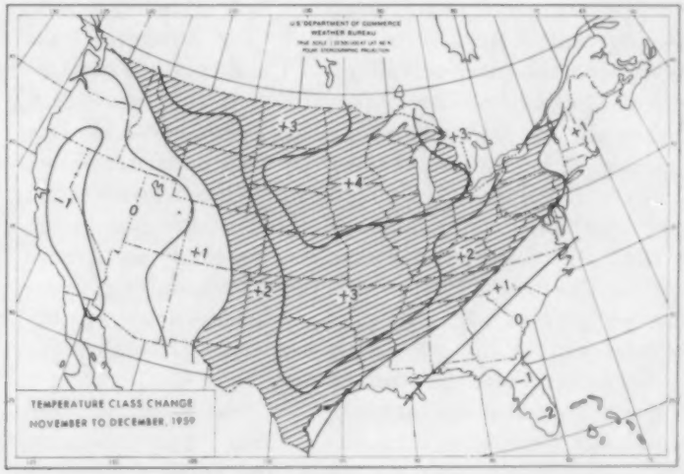

FIGURE 5.—The number of classes (out of 5) the surface temperature anomaly chan ed from November to December 1959. With the except on of Florida, much warmer temperatures dominated the country eastward from the Continental Divide. Temperature reversals of this magnitude and extent are uncommon between this pair of months.

Thus a long period of sustained cold in the northern Plains was abruptly terminated in December, and an equally remarkable period of persistent warmth was inaugurated. In fact, December averaged warmer than November in an absolute as well as an anomalous sense over a wide area embracing the Central States from Kansas northward. This constitutes a rare event indeed, and for many stations was a first occurrence. At Rapid City, N. Dak., for example, December's average was 6.3° F. warmer than November's. At a rather long list of stations including Duluth, Minn., Huron, S. Dak., Devils Lake and Bismarck, N. Dak., Burlington and Waterloo, Iowa, this was the first time in 60 years that December averaged warmer than November, with the difference amounting to a sizable 4° F. at the first three locations listed.

TABLE 1.—*Departure from normal of mean maximum and mean minimum temperature for December 1959 at selected western stations.* (°F.)

Station	Departure from normal	
	Maximum temp.	Minimum temp.
Winnemucca, Nev.	+4.4	−13.5
Salt Lake City, Utah	0.0	−6.5
Red Bluff, Calif.	+6.1	−3.1
Fresno, Calif.	+5.1	−4.0
Pocatello, Idaho	+3.2	−4.4

The mild weather was also remarkably persistent as the temperature at several stations remained above normal each day of the month. This was true at Fargo and Bismarck, N. Dak., St. Cloud, Minn., and Huron, S. Dak., to list a few. The variability on 5-day mean maps over Montana and the Dakotas consisted mainly of changes between the above and much above normal temperature categories.

Figure 5 depicts the change in mean temperature class [1] from November to December. The extensive area of hatching indicates the region over which the monthly temperature increased by two or more classes. Cooling was restricted to Florida, the western Great Basin, and the interior valleys of California. Temperature oscillations of this type, although they do occur, are rarely of this magnitude in December. In this instance, temperatures changed by two or more classes at 63 percent of the cities, a figure which has been exceeded only once since computation of this statistic was begun in 1942 [3]. Interestingly enough this single occurrence was in December 1958 when the corresponding figure was 68 percent [4]. On that occasion, however, the reversal was in the opposite sense, with December the colder rather than the warmer month.

Below normal temperature in the Great Basin occurred principally because of nocturnal cooling. Daytime maxima were actually above normal, and these apparently were more representative of the prevailing mild Pacific air masses because the mean temperature at the 700-mb. level averaged 3° to 4° above normal. Table 1 lists the departure from normal of average maximum and average minimum temperature for several stations in the Plateau area and the interior valley of California. The latter are included because the radiational cooling effect there was quite similar, though insufficient in that case to offset daytime warming.

At Winnemucca, Nev., the average spread between the maximum and minimum temperatures amounted to 36.3° F., exceeding the normal diurnal range by 17.9° F. This remarkable difference illustrates the marked effect which shallow radiation inversions can exert even on monthly averages. In this case the average temperature was reduced sufficiently to make this December the coldest in 27 years, even though the average maximum temperature remained above normal, and not a single pronounced outbreak of cold Canadian air can be traced into that region during the month. This effect, which is favored by the light winds and clear skies accompanying the Great Basin anticyclone, has been noted on 5- and 30-day mean maps on a number of previous occasions, and a particularly pronounced case has been described by Ross and Vederman [5] from the point of view of daily activity.

The California coastal region continued to experience unusual warmth. Los Angeles, San Francisco, and San Diego all reported departures from the 1921–50 surface temperature normal of +3° or more. Thus the warm regime which began a few years ago and characterized each previous month of 1959 continued unabated into December. At San Diego and Los Angeles the mean annual temperature for 1959 broke the record for all previous years, though 1958 was a close second. At San Francisco, on the other hand, 1958 was the warmest year, with 1959 next. In any event, the normals currently in use appear to have been highly unrepresentative during recent years, as discussed by several authors (e.g. [1,6]).

Florida was the only other portion of the country where temperatures averaged below normal. This occurred mainly during the first of the month as the cold polar air which had dominated most of the country during November lingered in the Southeast. Florida experienced its coldest weather of the season during this period when temperatures dropped 8° to 10° below normal levels, and freezing conditions extended well into the interior of the peninsula.

The Alaskan circulation was dominated by a deep trough extending southward from an intense polar vortex (fig. 1). The associated anomalous northerly flow introduced extremely cold air from off the Arctic ice cap into western Alaska. At Nome the monthly mean temperature of −7.1° F. was 14.8° below normal, the coldest December since records began in 1907. In advance of the trough, on the other hand, conditions were generally milder than normal, and anomalously strong, onshore winds brought very heavy snows to coastal regions. Yakutat, for example, was buried under 84.9 in. of snow, and Anchorage experienced 31.2 in., nearly three times as much as the average.

PRECIPITATION

Precipitation was heavy over a broad band extending from the Southwest across northern Texas northeastward to New England (fig. 6). Several major storms followed this course, accompanied by gale winds, heavy rain or snow, and in some cases sleet and freezing rain. The first system, though relatively weak, crossed the California coast on the 9th and gave a foretaste of things to

[1] Temperature anomalies are divided into the following classes: much above and much below normal (12½ percent occurrence each) and above, near normal, and below (25 percent occurrence each).

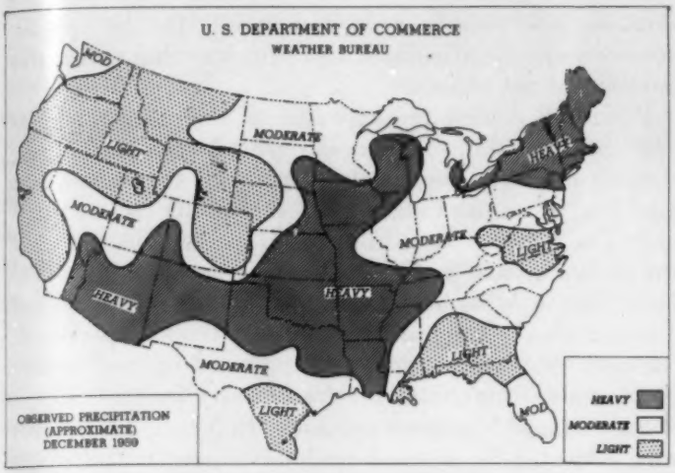

FIGURE 6.—Approximate observed precipitation for December 1959. (The classes heavy, moderate, and light normally each occur ⅓ of the time.) Unusually wet weather extended from Arizona eastward to the Texas-Oklahoma region, thence northeastward to the Lakes and the Northeast.

come by bringing snows of up to 10 in. in the mountain areas of central Arizona and New Mexico before moving on toward the east-northeast. Thereafter, three severe storms traversed roughly the same area, affecting the Southwest on the 13–14th, the 25–26th, and the 30–31st. As a result, precipitation was exceptionally heavy over Arizona, New Mexico, and portions of Oklahoma and Texas. Amarillo, Tex. established a new record with a monthly total of 4.52 in., and Phoenix, Ariz., a near record of 3.46 in. At Albuquerque, N. Mex., the accumulated snowfall of 14.7 in. established a new record for any month, exceeding by ½ in. the previous high value set in December 1958.

The rainfall released by these storms was particularly welcome over portions of the Great Basin and California where drought conditions had been developing for some time. However, at most locations, accumulations for the year continued substantially below normal, and additional moisture was badly needed. At some points, notably Reno and Winnemucca in Nevada, the drought actually intensified, and streams and reservoirs were either completely dry or at much below normal levels.

One of the most intense of these storms crossed the California coast on the 24th, produced a stormy Christmas in the southwestern United States, and subsequently headed toward the Great Lakes, bringing heavy snows and blizzard conditions over an extensive portion of the country from the mountain areas of Arizona across the Plains States to New England. The snowfall in Wisconsin in connection with this storm was the heaviest in 20 years, and in Rochester, N.Y., the ice damage was termed the worst in the city's history. In addition to heavy snows, sleet fell in the interior portions of the Northeast, and onshore, easterly gales generated heavy seas and caused widespread coastal flooding in Massachusetts on December 28 and 29. The region was

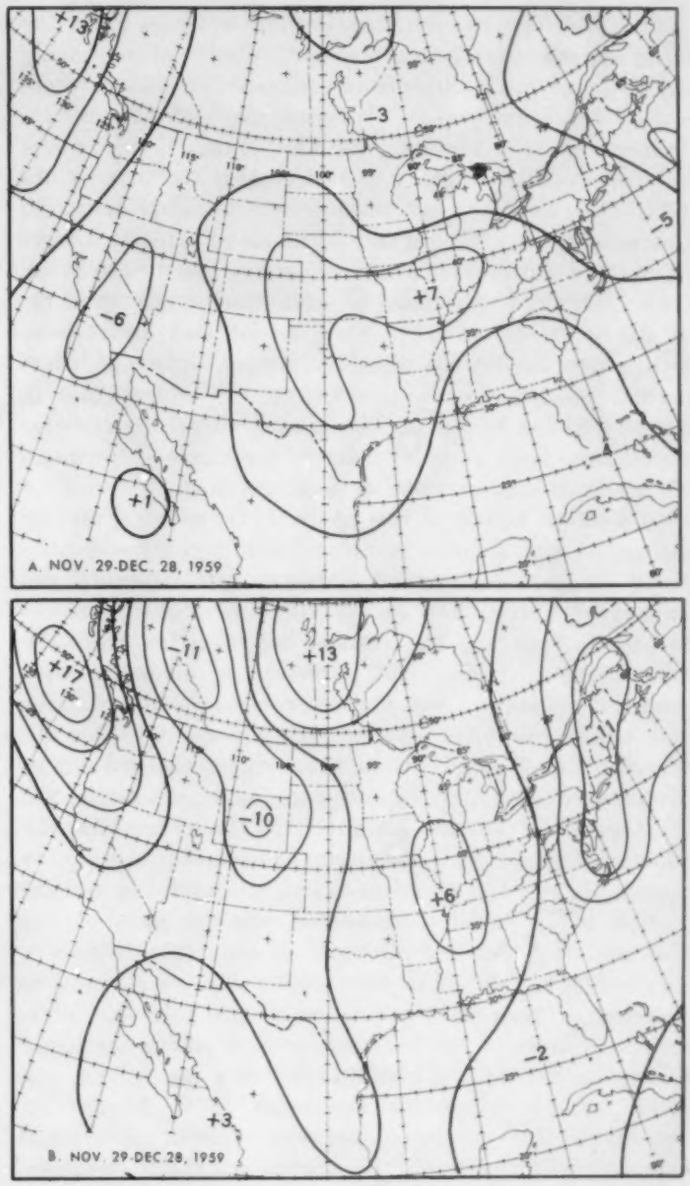

FIGURE 7.—(A) Estimate of the departure from normal of the 30-day mean vertical motion for December 1959 in units of mm. sec.$^{-1}$, with positive values indicating upward motion. This chart was calculated by applying the equivalent-barotropic model to the observed 500-mb. mean chart for December 1959 and to the normal 500-mb. contours for the month and taking the difference. (B) Estimate of the 30-day mean vertical motion for December 1959 in mm. sec.$^{-1}$ obtained by advecting the mean 850–500-mb thickness for the month with the observed mean 500-mb. flow.

declared a disaster area, and damage to coastal installations was estimated in the millions. The preceding disturbance also had been a heavy producer of snow in the southwestern Great Plains and of rain over most of the South. As a result of the two storms several streams in the lower Mississippi Valley approached or exceeded flood stage. Damages were relatively minor, for the most part, as the overflow was confined to low-lying agricultural areas.

Precipitation was subnormal in the Northwest under the mean upper-level ridge and was particularly deficient along the slopes of the Rockies from Colorado northward where warm, dry foehn winds prevailed most of the month. Typical of this regime was Cheyenne, Wyo., where only 0.03 in. fell to make this December the driest since 1905. Lee locations in Colorado were similarly dry, with Colorado Springs limited to 0.03 in. and Pueblo to a mere trace, thus ranking this month among the driest of all time. This is of particular interest, since stations not far to the south in northern New Mexico and Texas were setting new records for snowfall. Other regions of below normal precipitation occurred in the Southeast and in portions of the Virginias, a somewhat surprising circumstance since both areas lay near or in advance of the mean trough in an area of broad cyclonic curvature.

In a recent article of this series [7] the vertical motion associated with a mean monthly 700-mb. chart was computed using the Extended Forecast Section model described by Clapp [8]. This model is of the equivalent-barotropic type and the vertical motion arises from the assumption that the wind direction is invariant with height, necessitating certain divergence in the layers above and below the level assumed nondivergent. This divergence was shown [7] to be proportional to the relative vorticity advection at 500 mb. and the ratio between the wind speeds at 500 and 750 mb. To the extent that the equivalent-barotropic assumption holds, and it is probably reasonably satisfied on mean charts, the resulting vertical motion fields can be considered characteristic of the flow pattern. Since an estimate of orographic influence was not incorporated in this model, one should not be surprised if poor correspondence occurs over the intermountain areas of the West where such effects are likely to dominate. Such a computation was made from the mean 500-mb. chart for December 1959. Figure 7A represents the difference between values of vertical velocity computed from this month's 500-mb. contours and from the long-period normal. Comparison with the observed rainfall (fig. 6) reveals a fairly good similarity between the two patterns The wet area in the central Plains was associated with anomalous ascent, and the dry regions of the intermountain Northwest and the Southeast with subsidence (relative to normal). On the other hand, the very heavy precipitation over Arizona and the Northeast was poorly indicated, as was the unusual dryness in the leeward portions of Wyoming and Colorado. However, as has already been mentioned, the latter phenomenon can be attributed to foehn warming which this model does not simulate.

Figure 7B depicts the advection of the mean thickness field (850 to 500 mb.) observed during December 1959 by the mean 500-mb. flow for the month. If the mean thickness field is assumed stationary, the results can be interpreted in terms of vertical motion [7]. Also in this case, the resulting pattern (fig. 7B) bears a resemblance to the precipitation distribution, though again with marked discrepancies. The precipitation in the central portion of the country matched well with indicated upward motion (warm advection), but the very heavy rainfall in the Southwest and Northeast did not. In fact, the Northeast was subjected to marked cold advection in the mean. However, examination of the individual 5-day mean charts shows warm advection for relatively short periods prior to passage of storms, followed by relatively long intervals of cool advection, so that the latter dominated the monthly pattern. This emphasizes the difficulty encountered in attempting to specify a discontinuous parameter such as precipitation from smoothed charts in which the individual eddies are suppressed.

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CORRECTIONS

Volume 86:

p. 133: In the caption, the time for figure 1B should read "1200 GMT, May 27, 1958."

Volume 87:

p. 133: In figure 4, $\Delta T/\Delta t$ should be $-0.8°$ C. at 425 mb. and $-1.2°$ C. at 475 mb.

p. 134: In figure 5, $\Delta T/\Delta t$ should be $-0.8°$ C. at 475 mb. and $-1.4°$ C. at 625 mb.

p. 269: In column 2, first complete paragraph, change sentence to read "The lowest temperatures registered during this ascent were: $-89.5°$ C. ($-129.1°$ F.) at 17,000 m. on the way up, and $-90.9°$ C. ($-131.6°$ F.) at 16,500 m. on the way down."

p. 281: In column 2, line 2, the vertical motion value should be ± 1 mm./sec.

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U.S. DEPARTMENT OF COMMERCE • WEATHER BUREAU

The Weather Bureau desires that the *Monthly Weather Review* serve as a medium of publication for original contributions within its field, but the publication of a contribution is not to be construed as official approval of the views expressed.

The issue for each month is published as promptly as monthly data can be assembled for preparation of the review of the weather of the month. In order to maintain the schedule with the Public Printer, no proofs will be sent to authors outside of Washington, D.C.

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